Craig C. Sheaffer • Kristine M. Moncada

Introduction to Agronomy

Food, Crops, and Environment

SECOND EDITION









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Craig C. Sheaffer and Kristine M. Moncada

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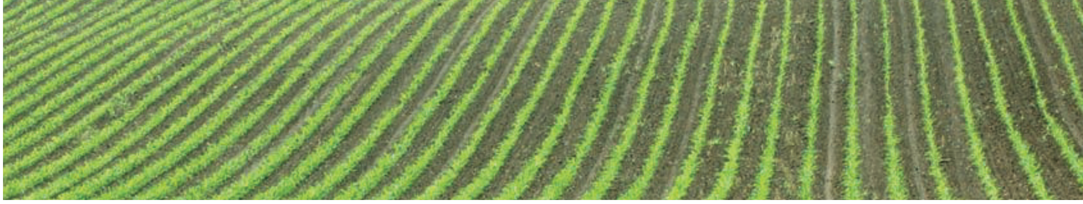
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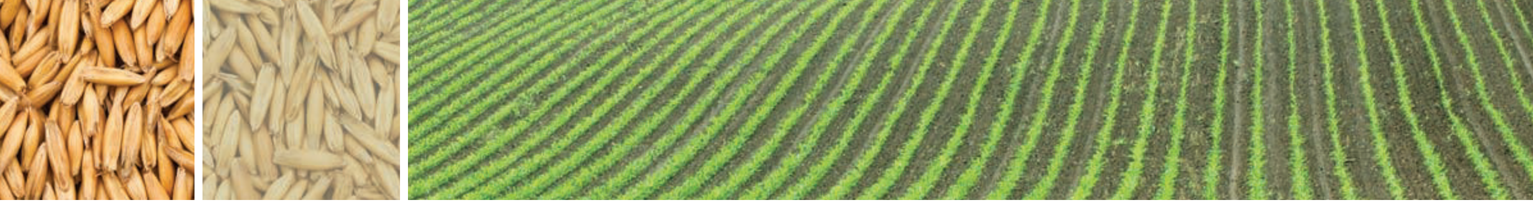
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Contents





Preface

Our writing was inspired by the opportunity to educate students on the importance of agriculture in food production, its economic value, and its use and impact on nonrenewable resources. Because many of our food products are highly processed and contain a mixture of ingredients, we often lose sight of their crop origin. Could pizza be made without flour from wheat or without cheese from cows fed corn and alfalfa? We also wanted to show that our crops are grown as components of agroecosystems that have replaced natural ecosystems on a large portion of our landscapes.

The production of food and fiber through agriculture began more than 10,000 years ago and is continuing today. Agriculture has changed from a necessity for production of food for survival of families to an industrialized business that produces raw materials that are processed into food, fuel, or industrial products. Agriculture is a significant contributor to the economy of the United States, and exports are important to feeding people in other areas of the world. Though more than 90 percent of the U.S. population was at one time directly involved in agriculture, today only 2 percent of the population is involved. Likewise, a population that was at one time mostly rural and familiar with the seasonal comings and goings of agriculture is now mostly urban and often annoyed by the smells, noises, and dust produced by farming activities. A dependable food and fiber supply is critical for the security of our country, and therefore farming is still one of our most important occupations.

Agricultural practices have changed the native vegetation in most regions of the United States. Agriculture is now the largest user of land as well as our soil and water resources. Sustainable use of these resources is imperative for productive agriculture in the future. Those involved in agriculture must also consider its impact on factors such as air and water quality that directly impact our whole society.

This text is intended as an introduction to plant science, crop science, and agronomy. Though many important technical aspects of crop production are discussed, the text is also intended for a broad group of students who may not have a background in agriculture. As generations go by, fewer and fewer students have a linkage to the farm. For example, grandparents, who may have raised wheat on their farms for breadmaking, now have grandchildren who depend on convenience stores to supply bread or snacks made of wheat. Though it is uncertain how many students will be directly involved in crop and livestock production in the future, an understanding of the source of food and its production is essential for all citizens.

The text begins with an historical view of agriculture, describing changes in farming that have occurred in the last 500 years. It discusses the industrialization of agriculture and the structure and economics of modern farming. Because of the interconnection of food and agriculture, we discuss the food that is consumed, crop sources of food, and changes in food-consumption patterns.

Our existence on the earth depends on plants, and the second part of this text deals with increasing our understanding of the nature of plants. We study their unique morphology, chemistry, and physiology. Plant morphological and physiological features enable plants to adapt to diverse environments. We also study how plants have been domesticated and improved through selection and breeding. Genetically engineering for traits such as herbicide tolerance and insect resistance is the latest approach to plant improvement.

Bountiful agricultural production in the United States is largely due to the presence of favorable climatic and soil resources. We learn about the variations in light, water, and temperature resources, how they affect plant growth, and how they are managed for crop production. The soil is a particularly valuable resource, and we study its use and conservation. We examine the concept of natural ecosystems that formed under the prevailing climatic and soil conditions. We contrast ecosystems with modern agriculture, and describe the impact of agriculture on the environment.

Crops and livestock are produced in agroecosystems that are managed with inputs of energy, chemicals, and improved plant genetics. There is a diversity of cropping systems and production practices used throughout the United States. We discuss crop rotation, crop fertilization, crop establishment, pest control, and crop harvest. Included in this second edition is a chapter dedicated to the growing area of organic agriculture. Weeds, diseases, and insects are problems for production of all crops and a significant cost of production. We discuss their natures and diverse approaches for their control.

Crop profiles review the important crops that are used for production of food, fiber, and fuel. Corn and wheat are the leading cereal grains and are used for human and livestock foods. Corn is now being grown for production of ethanol for use as a renewable transportation fuel. Legumes such as soybean and field bean are valued as oil and protein sources. Forage crops such as alfalfa and perennial grasses are used for livestock feed and also provide significant soil-conservation advantages.

Using examples of current issues affecting agriculture, this text provides illustrated, introductory information and explanations with references and links for further learning. Also, references to Internet sites provide considerable detailed information on production of crops adapted to specific states. In addition to review questions at the end of each chapter, critical thinking questions are included that require the student to think analytically. This text should also serve as a reference on agriculture for the general public.

New to This Edition

The second edition of this text contains many new features. Among the highlights—color photographs and figures throughout the entire text, a new chapter on organic agriculture, updated agriculture statistics, more review and critical thinking questions, tables with English and metric units, and expanded coverage of many topics. Specific additions to each chapter include the following:

Chapter 1

- The Columbian Exchange, which resulted in movement of crops from the Old to the New World
- Agriculture of the Anasazi, a highly organized Native American society that flourished years before the arrival of Columbus

Chapter 2

- Expanded discussion on the Conservation Reserve Program (CRP) and the Wetlands Reserve Program (WRP)
- Land capability classification
- The current Farm Bill

Chapter 3

- Profile of Norman Borlaug, Nobel Prize winner and father of the Green Revolution

Chapter 4

- Descriptions of medicinal plants, psychoactive crops, and toxic plants
- Profile of plants in the Nightshade family that contain alkaloids that affect human and animal health

Chapter 5

- Enhanced discussion of bioenergy crops including starch-based ethanol, biodiesel, and cellulosic ethanol

Chapter 6

- Careers and opportunities in food science

Chapter 7

- Sections on plant hormones that greatly affect plant responses to environment
- Determinate and indeterminate plants

Chapter 8

- The scientists who discovered phytochrome, a pigment sensitive to changes in day-length
- Growing degree days, a concept discussed as it relates to plant growth

Chapter 9

- Breeding perennial grains to provide food and ecosystem services
- The use of Roundup Ready alfalfa and challenges to its use by environmental groups
- Marketing of crop varieties

Chapter 10

- Expanded discussions of flooding, irrigation, artificial drainage, and the Colorado River watershed
- Crop insurance programs that reduce risks to farmers

Chapter 11

- How agricultural practices affect carbon sequestration
- Carbon trading as an approach to limit CO_2 emissions

Chapter 12

- Crop productivity index to assess the suitability of soils to produce crops
- Best practices for fertility management

Chapter 13

- Enhanced discussions of rotations, mixed cropping systems, and agroforestry
- Morrow Plots, the oldest rotational experiments in the United States
- Riparian buffers and shelterbelts as approaches to ensure the diversity of crops on landscapes, while providing ecosystem services

Chapter 14

- Strip tillage, a conservation-tillage approach
- Crop-production variables including row spacing and planting dates

Chapter 15

- History of atrazine and the controversies that surround it
- Weed resistance to Roundup, the most widely used herbicide today

Chapter 16

- Ug99 stem rust, a worldwide threat to wheat
- Biological control of soybean aphid

Chapter 17

- How to measure forage moisture content
- Strategies for harvesting cotton, tobacco, sugar beets, and potatoes

Chapter 18

- New chapter on organic agriculture, a small but rapidly growing farming method
- Content includes: organic certification, organic requirements, organic amendments, growth of organic agriculture, why producers farm organically, organic yields and profits, weed control, fertility, and organic livestock practices

Chapter 19

- The National Corn Growers Association
- Description of pseudocereals, cereal grains from nongrass crops

- Enhanced discussion of cool-season grasses such as tall fescue and warm-season grasses such as Bermuda grass and bahia grass
- Switchgrass use as a biofuel crop

Chapter 20

- The Soybean Growers Association
- Comprehensive section on soybean uses in food products
- Expanded discussion of additional grain and forage legumes including field peas, lentil, lupine, chickpea, faba beans, cowpeas, kura clover, crimson clover, and berseem clover

Chapter 21

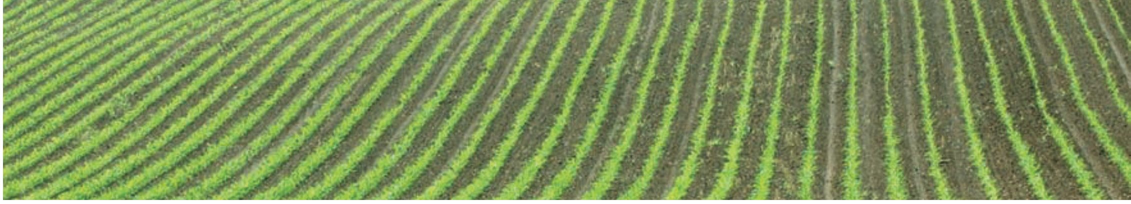
- Expanded discussion of cassava, true yams, plantains, taro, tobacco, cotton
- The production of opium poppy, a psychoactive crop



Acknowledgments

In addition to the many people who contributed to the first edition of this text, we would like to thank Matthew Leavitt, Dr. Lee DeHaan, Karl Jung, and the Rodale Institute for their research and/or writing contributions; Dr. John Lamb, Dr. Jeff Coulter, and Brillion Farm Equipment for photos or figures; and Scott Schroeder and Ruth Burke for assisting with the manuscript preparation. We also would like to extend our gratitude to the editors at Cengage including Benjamin Penner, Marah Bellgarde, Elizabeth Hough and Scott Royael. As always, we want to declare our tremendous appreciation of our families for their continuing patience and support throughout the writing of the two editions.

We are thankful for the efforts by all the market reviewers and second edition draft reviewers. In addition to their constructive criticism, they had many positive comments that lifted our spirits in completing this edition.

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Craig C. Sheaffer is a professor in the Department of Agronomy and Plant Genetics at the University of Minnesota, St. Paul. He received his BS at Delaware Valley College, Doylestown, PA; and MS and PhD degrees at the University of Maryland–College Park. He has studied sustainable cropping systems for more than 30 years. He is a fellow in the American Society of Agronomy and the Crop Science Society. His research has focused on forage production, pasture improvement, organic crop production, and bioenergy crops. He is particularly interested in using legumes such as alfalfa, kura clover, and Illinois bundleflower for livestock nutrition and soil conservation, and to supply biologically fixed nitrogen for other crops.

Craig has been involved with an active teaching program at Minnesota. He received the College of Food and Natural Resources distinguished teaching award in 2006. He teaches several courses to undergraduate and graduate students. These include an introductory course, "Crops, Environment, and Society," for agricultural students; an introductory course, "A Horse in Your Backyard," for those interested in horses; and a course for advanced undergraduates and graduate students, "Issues in Sustainable Agriculture."

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Kristine M. Moncada is an assistant scientist in the Department of Agronomy and Plant Genetics at the University of Minnesota, St. Paul, where she contributes to agricultural research and to developing educational materials. In 2010, she coedited *Risk Management Guide for Organic Producers,* a publication for organic farmers in the Upper Midwest. She has coauthored two interactive computer-based learning modules—"Forage Legume Identification" and "Forage Legume Morphology"—for the Crop Advisor Institute at Iowa State University. She also assists in teaching undergraduate agronomy laboratory courses at University of Minnesota. Kristine has a BS in ecology and an MS in applied plant sciences, both from the University of Minnesota. Her previous research has included characterizing the genetic diversity of native plants in Minnesota including purple prairie clover, spotted Joe-pye weed, and prairie cordgrass."



CHAPTER 1



History of Agriculture





Key Concepts

- Agriculture has been instrumental in the development of human civilizations.
- Crop and livestock species were domesticated in many regions of the world, the earliest being in the Fertile Crescent, which includes Mesopotamia.
- Prior to European colonization, many Native American cultures developed agriculture as the primary food source. Corn, squash, and beans were widely grown.
- The Columbian Exchange of plants, animals, and microbes resulted in significant food, cultural, and ecological changes in both the Old and New Worlds.
- Agriculture in the United States has evolved from subsistence-level farming by early colonists to an efficient production system where food is abundant.
- Improved productivity with reduced manual labor has occurred because of the application of mechanical, chemical, and plant-breeding technology.

Key Terms

agrarianism
agriculture in the United States
Columbian Exchange
domestication
Fertile Crescent
Homestead Act of 1862
hunting and gathering
Mesopotamia
precision agriculture
subsistence agriculture
xenia effect

Introduction

Our current agricultural production system is built upon numerous human experiences from the past 200,000 years. For most of human existence, **hunting and gathering** of food—"living off the land"— was a preoccupation and a necessity for survival. The crops that provide the primary food sources for our societies today were first domesticated approximately 10,000 years ago at the end of the last ice age. That domestication was concurrent with the first agriculture and the start of human civilizations. Modern **agriculture in the United States**—the practice of cultivating land to raise food, livestock feed, fiber, or fuel from crops or livestock—has been shaped by human struggles, technological developments, and government policy. Technology, such as machinery, fertilizer and pesticide chemicals, and improved animal breeds and crop varieties, has greatly increased agricultural productivity. It has led to larger farms, and fewer farms and farmers.

Human Beginnings

The exact number of years that humans have walked the earth is unknown. Scientists estimate that modern humans lived in Africa 200,000 years ago. From Africa, the pathway of human migration has been traced to Europe and Asia. From Asia, multiple migrations of early humans likely crossed from Siberia to present-day Alaska about 20,000 to 25,000 years ago during the last ice age in North America (Figure 1-1). The trip may have occurred via water in small boats or over land. Water accumulation in mile-high glaciers resulted in the reduction in sea levels and the emergence of the Bering Land Bridge. The 18-mile (29-kilometer) trip to Alaska across the land of this now submerged region was very manageable for these nomadic people.

Migrating down the seacoast and possibly on land, these travelers colonized the western North American coast and reached the furthest latitudes in South America roughly 12,000 to 20,000 years ago. From the coast, these earliest Native Americans migrated inward and populated the interiors of North and South America. It is likely that these early travelers relied on seafood, land animals, and plants as sources of nutrition. They encountered now extinct, huge, woolly mammoths and giant sloths. These early humans were not Neanderthals and possessed essential knowledge for surviving as well as hunting and gathering. They used weapons and simple tools.

Native Americans dispersed throughout the western hemisphere with an initial preference for warmer regions. By the time of Christopher Columbus's first voyage to the Americas in 1492, the native population was more than 70 million. Most lived in Central and South America with roughly five million people living in what is now the United States.

Hunting and Gathering

A characteristic of these native people was that they depended on hunting and gathering—"living off the land"—for survival. Because of their dependence on the earth for sustenance, they had a respect and reverence for nature. They were not materialistic and land ownership was rare. Hunting and gathering systems were

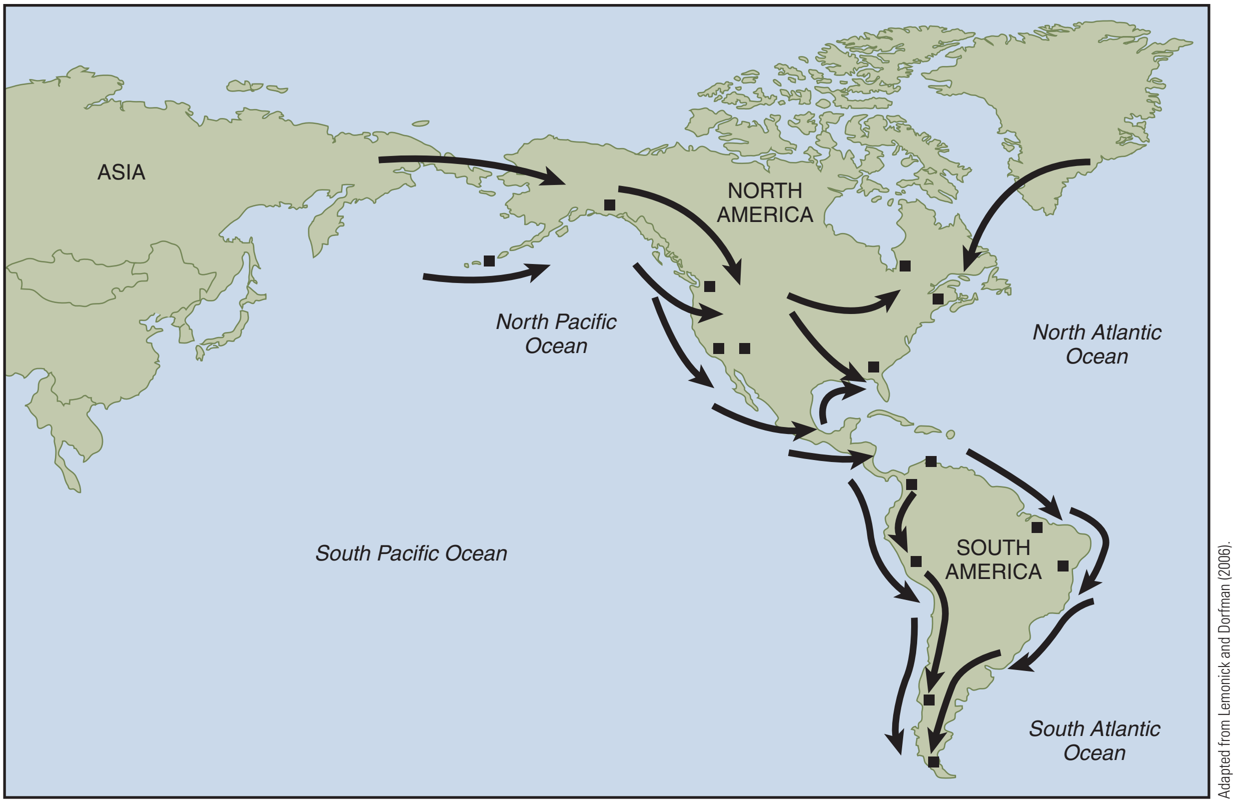


FIGURE 1-1 Potential early paths of settlement of North and South America. The squares indicate archeological sites that have been found.

reliable and basic. Hunters and gatherers had a diverse diet, and starvation was rare because they did not depend on the cultivation of a limited number of crops or animals. It is likely that hunters and gatherers actually worked less and had a less compulsive lifestyle than modern humans. When early human societies developed crop cultivation, a larger population could be fed, but a more labor-intensive and regimented lifestyle was necessary.

The habits of hunters and gatherers were influenced by the climate as well as plant and animal resources in a region. The relative proportion of meat compared to plant products consumed by hunters and gatherers also varied with the climate and region. In North America, hunters and gatherers ate mostly plant foods with meat and fish accounting for at most one-third of the total diet. Plants were essential because they undoubtedly provided continuity in food supply, whereas the availability of meat was dependent on the success of a hunting or fishing expedition. The survival of hunters and gatherers depended on considerable knowledge of their environments.

Knowledge of the Seasons and Nature

Hunters and gatherers understood how changes in the seasons affected the migration of animals and the maturation of plants. For example, northern woodland Native Americans knew about collecting maple syrup in the spring, gathering wild

rice and nuts in the fall, and the migration of ducks and geese prior to winter. They knew they needed to store food in order to survive the winters. Families and tribes also seasonally migrated to be near food sources and had semipermanent camps and dwellings. For example, some Native Americans living in the North American plains—such as the Crow, Kiowa, and Sioux—moved their camps to be near the great bison herds that provided essential meat and hides. In the fall, the Ojibwe of northern Minnesota moved to camps near lakes and rivers to harvest wild rice, an essential ingredient of their winter diet.

Botanical Knowledge

Hunters and gatherers knew about using plants as food sources as well as for medicinal and ceremonial purposes. It is likely that this botanical knowledge resulted from a trial and error process with the knowledge being passed down orally from generation to generation.

Plants as Food

Hunters and gatherers had a unique knowledge of plant food sources and when to harvest them (Figure 1-2). They also knew that some foods, such as acorns and cassava, needed to be boiled or baked to become edible. Plant foods were often processed so that they could be stored. Berries and fruits were dried for winter consumption, and grains were separated from the chaff and ground between stones into flours. Examples of plant-derived foods in northern regions of North America included:

- Grass seeds: Wild rice, wheatgrasses, and wild rye
- Forb seeds: Lambsquarters, bulrush, and wild sunflower
- Roots, tubers, and rhizomes of plants: Jerusalem artichoke, hog peanut, arrowhead, bulrush, and wild licorice
- Nut trees: Hazelnut, hickory, chestnut, and oak



Minnesota Historical Society.

FIGURE 1-2
Native Americans had a unique knowledge of plant food sources and when to harvest them. Left, prior to harvest, the wild rice was tied into bundles.

- Fruits and berries: Wild plum, wild cherry, crab apple, blueberry, cranberry, and wild strawberry
- Vegetables: Milkweed flowers and shoots, young cattail shoots and rhizomes, and upper leaves of lambsquarters
- Sweeteners: Sap from maple trees and flower nectar from common milkweed

Medicinal Plants

In northern regions, some plants or plant parts were used not only for medicinal purposes, but also as poisons and therefore as potential weapons against enemies. The following are examples of plants used for medicinal purposes:

- Joe-pye weed, which is a tall annual forb that grows in wetlands or poorly drained soils. It contains several compounds including alkaloids. It was used for treatment of kidney and urinary tract problems.
- Milkweed, which is a perennial that grows in prairies and margins of woods. It has purple flowers that produce pods containing silky seeds. A white milky sap is produced from the vascular system when stems or leaves are broken. Milkweed was used as a diuretic and in the treatment of other urinary tract problems. It also was applied to ringworm, poison ivy, and warts. Milkweed is also food for the Monarch butterfly.
- Stinging nettle (itchweed), an herbaceous perennial that is most frequently found in damp, rich soils and woodland margins. It can be identified by the stinging hairs located on its stems and leaves. These hairs contain acetylcholine, histamines, and other chemicals that can cause rash and itching. The cooked herbage and tea were used to reduce internal and external bleeding, and the roots were used as a diuretic.
- Jewelweed, or touch-me-not, which is a succulent broadleaf that can grow to a height of 5 feet (1.5 meters). It is found in moist woodland areas. It contains tannins, lawsone (a red-orange pigment), and other compounds. The whole jewelweed plant was crushed and applied to burns, poison ivy rash, sunburn, insect bites, and ringworm.
- Wild bergamot (beebalm), a perennial mint with a square stem and purple-pink flowers born at the top of the 1–3 foot (0.3–0.9 meter) tall stems. It is found in native prairie. Bergamot contains essential oils, and its herbage was used for the treatment of respiratory problems, headaches, burns, and insect bites. Extracts of the roots were used to treat constipation and stomach pains.
- Blue flag, a beautiful native perennial that thrives in wet meadows. Its rhizomes contain oils, resins, and acids. Blue flag is quite toxic to humans and even touching its sap can cause blistering of the skin. It was used externally to treat sores and wounds because of its antimicrobial properties. Native Americans dried the rhizomes and consumed them internally for use as a diuretic and a laxative.
- Water hemlock, which is a plant found in wet, swampy areas of the Great Plains. It contains a poisonous resin and an alkaloid that is concentrated in the tubers at the base of the stem. Ingestion of a pea-sized piece of the tuber can cause death in humans. The plant has been used to treat convulsions and epilepsy, but extracts were also used as a poison on the tips of arrows.

Although these species have been used in the past by Native Americans, one should always use caution (and a good field identification guide) when consuming or applying wild plants or extracts.

Vegetation Manipulation

Some hunters and gatherers used periodic burning to actively manage vegetation. Native Americans burned forests of eastern North America and the tall grasses of the prairies so they could create new growth to attract bison, deer, and antelope that were then hunted. They also used burning to suppress undesirable vegetation and to provide an environment favorable for growth of food plants. Burning of plant herbage also increased the availability of nutrients to crops.

Hunting Strategies

Hunters successfully killed both large and small game, and they fished. For example, Native Americans on the Great Plains had strategies to stampede herds of bison into ambushes and over cliffs, where injured animals were quickly killed. Some cultures set fires to cause animal stampedes. They also used calls for moose and waterfowl. They dressed in the skins of deer and bison while stalking these animals. A number of weapons were developed including snares, bows and arrows, slings, and spear throwers. Hunters and gatherers consumed flesh from the dead animals that were killed by drowning or falls. Native Americans also harvested fish, frogs, and shell fish as food sources.

Clothing and Shelter

Native Americans hunted and trapped a diversity of animals to provide themselves with clothing made of fur and hides. Hides from bison and deer were also used for building shelters, such as tipis. Willow twigs and branches were commonly woven over heavier timbers to provide a foundation for applying mud to make earthen lodges. In northern regions, birch bark was commonly used for canoes, baskets, dishes, and sometimes artwork. Native grasses were used for basket weaving.

Development of Agriculture

After the last ice age about 10,000 years ago, agriculture, including the domestication and cultivation of crops and animals, developed in several regions of the world. **Domestication** is the adapting or taming of wild species of plants or animals to be used by humans. Agriculture went along with the first, large, permanent human settlements and the origins of modern civilizations. It is important to note that the discovery of agriculture as an approach to meeting food needs was a gradual process likely lasting thousands of years. Early farmers probably grew limited quantities of some crops on purpose while still hunting and gathering to meet their food needs. The reasons why crop domestication and cultivation

occurred were undoubtedly different throughout the world. Some of these reasons were:

- Crop cultivation was necessary to achieve a secure food supply during a time when climatic changes made many areas of the world inhabitable and sedentary populations were increasing, especially adjacent to waterways and other favorable habitats. Farming required more labor than hunting and gathering, but, when successful, it fed a larger population. Once the transition from hunting and gathering to agriculture had occurred and populations had increased, cultures became dependent on farming.
- Climatic changes including warmer average-global temperatures resulted in favorable growing conditions for increased distribution and growth of cereals like rice, corn, and wheat, which were the basics of early civilizations. People used these grains as a critical source of energy. The grains could be ground and cooked for immediate consumption, they could be baked into breads for later consumption, or they could be stored.
- Similar to how human social cultures have changed, the transition to crop cultivation was a natural step in cultural evolution beyond hunting and gathering. Accumulated knowledge of how to grow plants and animals resulted in the development of agriculture. Likewise, technology was developed that enabled harvesting (e.g., the sickle), milling, and processing of large quantities of grain.



Crop Domestication

The first crop domestications occurred as a result of selection for certain traits in the plants by early agriculturalists. Some of the selection criteria for grain crops were:

- Increased plant yield: Farmers saved seed from plants that were more robust and had greater grain yield.
- Increased seed size: Small seed size can be an advantage in the spreading of seed and in reestablishment, but larger seeds are easier to harvest, clean, and grind. Large seeds also produce bigger plants.
- Nonshattering seed: Shattering is a natural process in which seed falls from a plant soon after ripening. Selection for nonshattering seed allowed more of the seed to be harvested.
- Naked seed: Newly harvested seed of some grains, such as barley and oat, is normally protected by seed coatings (see Chapter 7). Selection for seed without these coatings allowed for easier processing.
- Reduced seed toxins: Some seeds contain toxins to prevent consumption by wildlife, and they also may be toxic to humans. Selection for reduced toxin levels allowed for further use by humans.

Archeologists have uncovered sites throughout the world where early farmers practiced agriculture and where these same early farmers domesticated the first crops and animals. These sites revealed not only early agricultural practices, but also some aspects of the societal relationships among humans.

The Fertile Crescent

The **Fertile Crescent** is the earliest site where crop and animal domestication occurred. It extends from the eastern coast of the Mediterranean Sea to the Persian Gulf (Figure 1-3). The region includes the present-day countries of Egypt, Iraq, Iran, Jordan, Israel, Palestine, Turkey, Lebanon, and Syria. In this region, farmers domesticated wheat, barley, pea, date, olive, and fig plants, as well as goats, sheep, pigs, and cattle.

Within the Fertile Crescent was an area surrounding the Tigris and Euphrates Rivers called **Mesopotamia**, or the "land between two rivers." Mesopotamia was a flat flood plain bordered on the north by the Zagros Mountains and on the south by the Arabian Desert. This was an optimum site for the development of agricul- ture because of its environmental diversity induced by geography and the Persian



FIGURE 1-3
The Fertile Crescent (in light gold) was a site for early domestication of crops such as wheat and barley, and livestock such as pigs, goats, sheep, and cattle. Mesopotamia (in dark gold), between the Tigris and Euphrates Rivers in present-day Iraq, was the site of one of the earliest civilizations.

Gulf. The climate was mild and the growing season long. Rich alluvial soil filled the river valley, and abundant water met the needs of humans and crops. It is called the cradle of civilization and was the site of the ancient Sumerian civilization (~5000 BCE) that was later followed by the Babylonian, Assyrian, and Chaldean cultures. The Sumerians developed huge cities of sun-dried brick that provided homes for millions. They were the first scientists and mathematicians, and they developed the wheel, calendars, astronomy, and writing. Agriculture was the foundation for the society, and the Sumerians raised crops of wheat, barley, vegetables, dates, figs, olives, and grapes. Crops prospered in this arid region because of a complex irrigation system using water from the Tigris and Euphrates Rivers. The Sumerians also kept cattle, sheep, and goats for meat; milked cows; and used oxen for plowing.

On the western edge of the Fertile Crescent along the Nile River, the great Egyptian civilization (~3500–700 BCE) that built the pyramids also developed sophisticated agriculture. Most Egyptians were farmers, and agriculture was the most important economic activity. They produced abundant crops, which they traded for metals and other goods. The Egyptians depended on the annual flooding of the Nile for fertilizing their lands, but they also developed sophisticated soil drainage and crop irrigation strategies. They developed simple cultivation tools, such as the plow and the metal sickle for harvesting crops. They grew a diversity of grain crops including wheat, barley, and rye. Their vegetable gardens included cucumbers, onions, and melons, as well as orchards of figs, grapes, olives, and dates. They grew flax and cotton, which were used to produce linen and other cloth. Dyes were developed to color fabrics. A diversity of livestock was used in agriculture including oxen, donkeys, sheep, goats, ducks, and geese. The Egyptians developed winemaking and food-preservation methods using smoking, salting, drying, and pickling, and they were among the world's first bakers of bread. They also created the first medicinal-plant, spice, and perfume industries.

East Asia

About 7000 to 8000 years ago, significant early agricultural civilizations developed around crop and animal domestication in China and Thailand. Along the Yangtze River system in southern China, people domesticated rice, and farming societies arose. The warm climate with high rainfall (more than 50 inches [127 centimeters] per year) facilitated the development of both short- and long-grained rice. Farmers grew rice in lowlands adjacent to the river as well as at sites on higher ground. They also domesticated pigs, poultry, and water buffalo. In northern China, agriculture developed along the Yellow River. In contrast to the southern region where rice developed, this northern region experienced harsh winters and drought in summers. People domesticated foxtail millet and broomcorn millet, and these grains became major food sources in this region. Later, soybeans were domesticated here as well.

Central and South America

In Central and South America, agriculture developed later than in the Fertile Crescent or Asian regions, but was the basis for several major cultures. The Inca civilization flourished and ruled in the Andes Mountain region, and the Mayan and the Aztec civilizations developed in the Mesoamerica areas of what are now Guatemala, Belize, and Mexico. Considerable archeological evidence indicates the

significance of the Mayan and Aztec civilizations. Both cultures developed large cities that included gardens and temples. The Aztec capital, Tenochtitlan, had a population of 200,000 at the time of its conquest by the Spanish. Both cultures wrote and used mathematics and calendars. The Aztecs also had books about astronomy, religion, and history.

The success of the Mayans and Aztecs was based on corn, beans, and squash. Maize (corn) was domesticated from 8000 to 9000 years ago in the Tehuacan Valley, 150 miles (241 kilometers) south of present-day Mexico City. We do not know the exact genetic origin of corn, but a relative, teosinte, is still found in the area (Figure 1-4). Later, farmers domesticated squash, beans, amaranth, chili peppers, and cotton in this same region. In the high altitudes of the Andes Mountains, potato and quinoa were domesticated as well as the llama and alpaca.

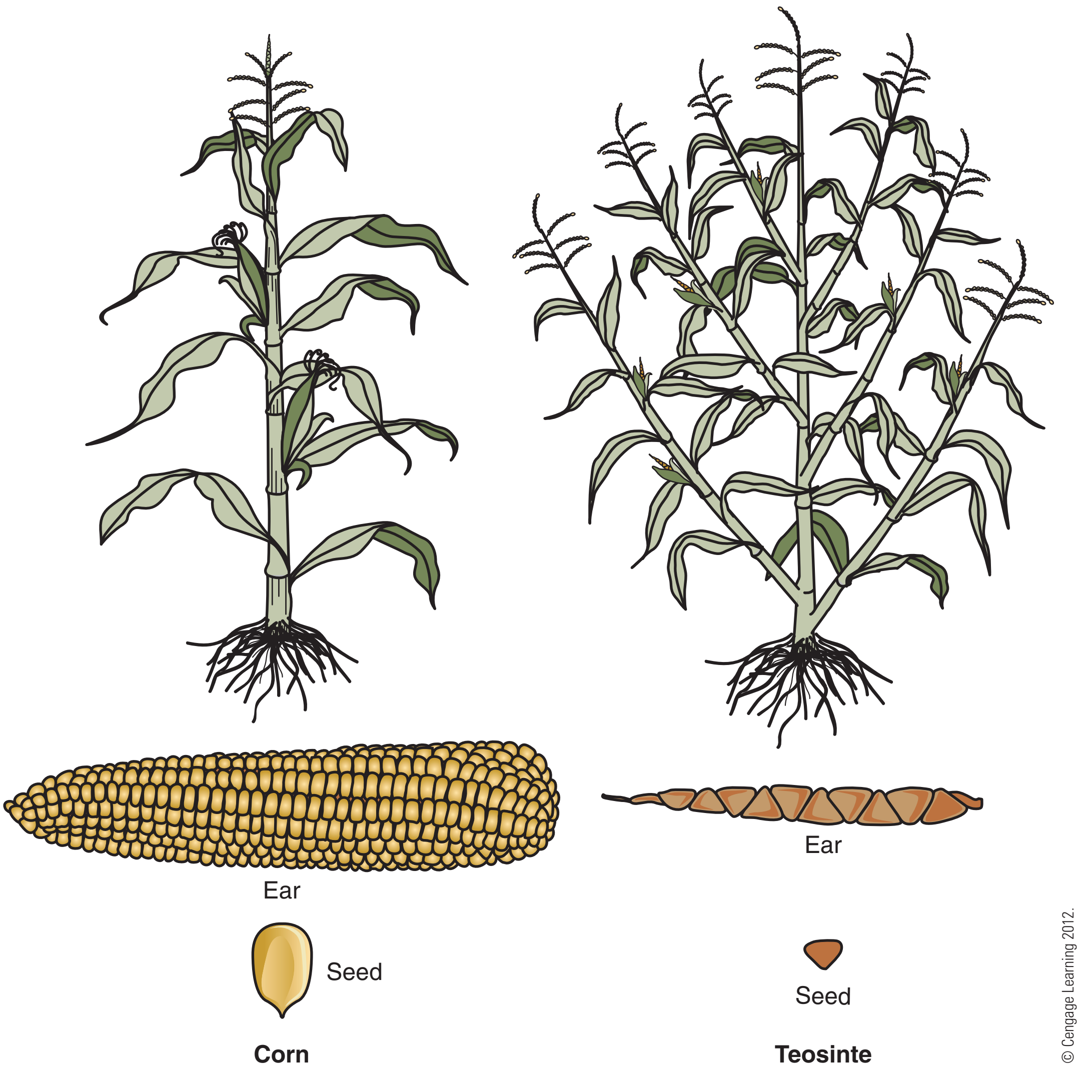


FIGURE 1-4 Farmers domesticated corn in the Tehuacan Valley in southern Mexico. These illustrations show the mature plant and seed of corn and one of its potential ancestors, teosinte. Modern corn is around 9 feet tall, while teosinte is around 12 feet tall.

Farmers domesticated at least four species of potato in the Andes region. Corn, beans, and squash traveled into North America from Central America by trade or by migration of Native American tribes. They were important food sources for many native cultures and subsequently for the early colonists.

Eastern North America

Roughly 3000 to 4000 years ago, native people living in the eastern region of what is now the United States domesticated squash and pumpkin. Remnants of these plants have been located in caves over a large region that includes present-day Tennessee to Arkansas in the south and from present-day Illinois to Ohio in the north. From 2000 to 2500 years ago, small food production communities emerged and grew these crops along streams and rivers. Other plant food sources included goosefoot, erect knotweed, and little barley (all high carbohydrate crops), and marsh elder, sunflower, and maygrass (all high in oil content). Inhabitants obtained protein from hunting and fishing. About 1000 years ago, corn became an important food crop in this region.

Other Crop Domestication

Farmers domesticated other important crops around the world (Figure 1-5). Scientists, including Nikolai Vavilov from what was then the Soviet Union, and Jack Harlan from the United States, were leaders in identifying crop origins. They identified centers of origin for crops based on the presence of great genetic diversity for a crop. These centers are still explored today as a source of plant traits, such as disease resistance.

Global Diffusion of Crops

Crops were successfully transported from one region to another by migrating people and by trading. Continuing changes in boundaries of empires and movement of conquering armies also affected distribution of crops and agricultural practices. One of the world's greatest cultures, the Roman Empire, domesticated no new crops or livestock, but it was responsible for the advancement of agriculture throughout its territories. Roman agriculturalists wrote about improved agricultural practices such as crop rotation and use of manures. Wheat was essential for making bread in all classes of Roman society, and it followed the Roman legions throughout their empire. Other Roman food crops included millet, turnips, olives, and figs. The Romans also grew alfalfa as food for their horses. During feeding, hayseed was widely, though accidentally, distributed.

American Agriculture

The explorations by Columbus in 1492 initiated the exchange of plants, animals, and microbes between the Old and New Worlds. This **Columbian Exchange**—first named by historian A. W. Crosby—that ultimately included triangular trade



North America
Plum, Pecan
Grape
Sunflower
Blueberry
Tepary Bean
Cranberry

Meso America
Maize (corn)
Cassava, Cotton
Sweet Potato
Tomato, Avocado
Common Bean
Sieva Bean
Papaya, Cacao
Scarlet Runner Bean

Highland South America
Common Bean
Lima Bean
Potato, Cotton
Peanut

Lowland South America
Yam, Cotton
Pineapple
Cassava
Sweet Potato

Europe
Rye, Oats
Sugarbeet
Cabbage
Grape
Olive

Africa
African Rice
Sorghum
Pearl Millet
Finger Millet
Watermelon
Cowpea
Coffee, Cotton
Sesame, Yam

Near East
Pomegranate
Chickpea
Wheat
Barley
Onion
Pea, Lentil
Fig, Date
Flax, Pear
Grape, Olive
Apple, Plum

Central Asia
Common Millet
Buckwheat
Foxtail Millet
Broadbean
Alfalfa
Hemp, Grape

China
Foxtail Millet
Soybean
Cabbage
Onion, Peach

India
Pigeon Pea
Eggplant
Cucumber
Cotton
Sesame

Southeast Asia
Oriental Rice, Tea
Taro, Thin Sugarcane
Banana, Citrus
Yam, Mango

South Pacific
Nobel Sugarcane
Coconut
Breadfruit

Australia
Macadamia Nut

FIGURE 1-5 Areas of crop domestication around the world.

between Europe, America, and Africa, led to significant cultural and ecological changes throughout the world (Figure 1-6). It included important food crops like corn, potato, sweet potato, and tomato moving to Europe, while crops like wheat, oat, white rice, forage grasses, and forage legumes were brought to the New World by colonists. On his first voyage to the Caribbean, Columbus discovered corn and returned with many varieties to Spain. He also introduced tobacco to Spain, which ultimately led to a smoking addiction in Europe. The Spanish brought the potato to Europe from the Andes region around 1550. Potatoes later became a popular crop in England and especially in Ireland.

There were few domesticated animals in the Americas except for the turkey, llama, and alpaca. Explorers and colonists brought livestock for food and for work. Horses that escaped, were traded, or were stolen from the Spanish were used for hunting, work, and warfare by Native Americans living on the Plains. In the original colonies, swine were a favored livestock of the colonists as they were able to adapt to a diversity of food sources. The successful adaption of swine to the New World is

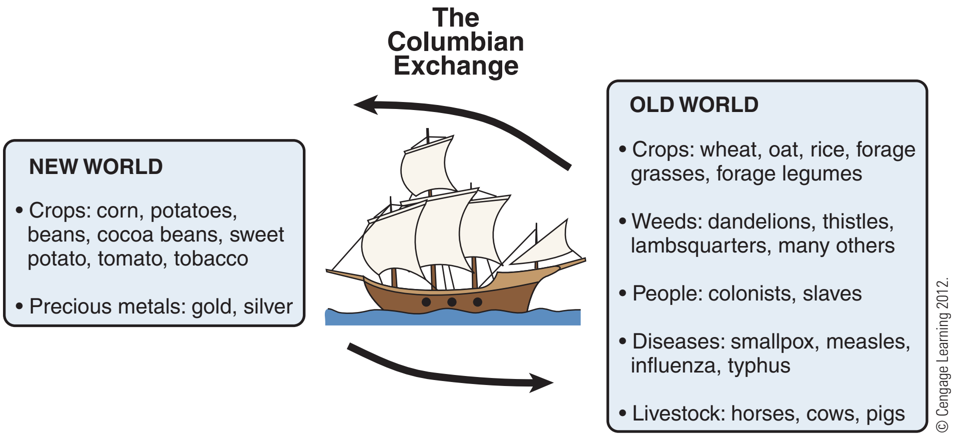


FIGURE 1-6
The Columbian Exchange. People, crops, livestock, and culture were exchanged between the Old and New Worlds.

evident in wild, feral populations that exist today. The Columbian Exchange initiated the collapse of many Native American cultures. They lost hunting and agricultural land during unscrupulous trading and warfare with Europeans. Most importantly, their populations suffered greatly from the influx of diseases, such as smallpox, from which they had no immunity. In addition, free-ranging cattle and swine destroyed Native American gardens and other food sources forcing Native Americans to move.

The Columbian Exchange radically changed the plant-based ecosystems in North America. In addition to many crop plants, Europeans also brought new plant species that became established as agricultural weeds. Some plants, like dandelion, lambsquarters, and absinthe, were originally brought as vegetables or for medicinal purposes; others, like thistles and nightshades, were spread through ships' ballasts and as contaminants in hay, bedding, and straw. Other invasive pests, like large black and Norway rats, stowed away on ships and became major threats to stored food supplies of colonists and Native Americans.

Native American Agriculture

When Europeans began to arrive in the 1500s, more than five million Native Americans were living in more than 500 tribes that were distributed throughout what is today the United States. Some of these tribes, such as the Blackfeet, Crow, and Dakota, were primarily nomadic hunters who lived in tipis and depended on the migrating bison for sustenance. Other tribes lived in more permanent villages and practiced agriculture. The sedentary lifestyle of the agriculturalists contrasts greatly with that of the stereotyped nomadic warrior tribes as depicted in movies of the Old West. Tribes had frequent interaction; agricultural tribes used their crops to trade with the hunting tribes for meat and hides. Like the first civilization in Mesopotamia, Native American villages were located in river valleys where the soil was rich and water was available for drinking and irrigation of crops.

Hidatsa Agriculture

The classic anthropological book *Buffalo Bird Woman's Garden* by G. L. Wilson provides a snapshot of traditional Native American agriculture. Published in 1917, the book describes traditional agricultural practices of the Hidatsa tribe as described by Maxi'diwiac, or Buffalo Bird Woman. Buffalo Bird Woman lived

from about 1839 to the early 1900s and was a member of the Hidatsa tribe whose culture was based on a combination of hunting and agriculture.

The Hidatsa practiced an agricultural tradition that traced back to 1100 CE in the Knife River-Heart River region of the Missouri River Valley of present-day North Dakota. Archeologists have identified that culture as the Plains Village society. In that society, women were the primary farmers with men participating only at special times such as at harvesting. In the early 1800s, the Hidatsa first encountered Canadian and American fur traders. Following white settler migration into the area, the Hidatsa were forced to abandon their traditional villages and resettle on a reservation in 1870. Much of their original land is now submerged by the waters of Lake Sacagawea created by the Garrison diversion dam on the Missouri River.

The traditional Hidatsa community consisted of permanent earthen lodges built on terraces by the Missouri River. The river provided fish, mussels, and waterfowl, and the Hidatsa used the rich floodplain bottomlands for extensive gardens. The Hidatsa hunted for bison, deer, and smaller mammals on the surrounding prairies, but crop-based agriculture was the food foundation for their culture. They also traded grains to other tribes, such as the Dakota, for meat from bison and deer.

Hidatsa agricultural practices reflected centuries of experimentation. They recognized that fertile bottomlands that were exposed to the river's floods were superior to the dry, sod-bound prairie as planting sites. Fields were initially cleared of brush by cutting and burning. The Hidatsa rotated crops among fields. They initially made tools from wood, antler, and bone, but later they used steel traded from European settlers (Figure 1-7). They practiced weed control, crop and seed selection to maximize yields, and crop storage. The Hidatsa grew nine types of corn, four types of sunflower, five types of beans, and squash. They cultivated a very strong tobacco and smoked it for ceremonial purposes; however, the tribe discouraged young Hidatsa men from using tobacco because they knew the substance made them short-winded and consequently poor runners and weak in battle.

Like many northern tribes, the Hidatsa grew the "three sisters"—corn, squash, and beans. These crops were often intercropped because they effectively used

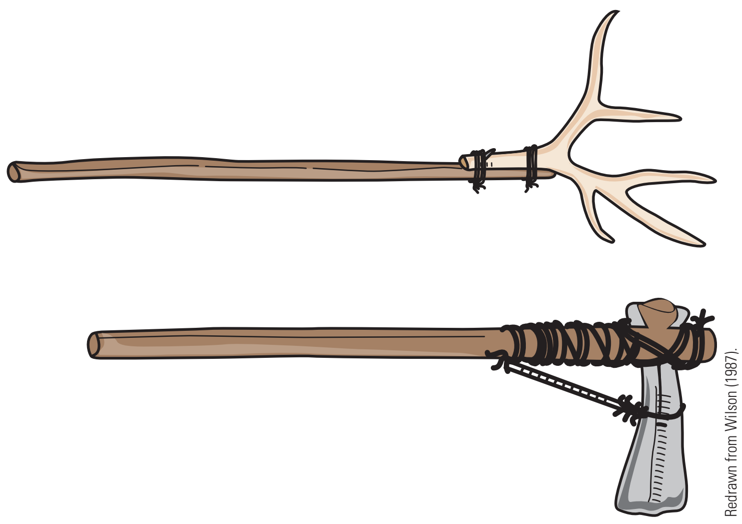


FIGURE 1-7
A rake and hoe used by the Hidatsa. The hoe has a wooden handle, and the blade is from the shoulder bone of a buffalo. The antler rake is from the antler of a deer attached to a wooden handle.

different resources; the corn grew tall, and the squash could climb it. Beans, a type of legume, could provide nitrogen that would be available to the corn crop. Nutritionally, the three crops provided for a balanced diet. The beans were a source of protein; the corn provided carbohydrates; and the squash was a source of vitamins. The Hidatsa planted corn in hills about 4 feet (1.2 meters) apart beginning in May. They planted about seven kernels of corn about 4 inches (10 centimeters) deep in each hill. They hoed the corn for weed control beginning when the plants were 3 inches (8 centimeters) tall and again when the corn silks appeared. The Hidatsa also erected scarecrows, and children occupied watchtowers to frighten away birds that threatened their crop (Figure 1-8).

Though the Hidatsa consumed some of the corn when it was immature in the form of sweet corn, most of the corn was allowed to dry and mature. They harvested corn ears with husks attached. Husking, shelling, and sorting the corn was a community event. It was important to segregate dried from unripe green ears. Corn for winter grain use was stored in underground pits, 5–10 feet (1.5–3 meters) deep (Figure 1-9). The Hidatsa saved harvested seed for planting the following spring and also observed the custom of putting away seed for two years for security in case of crop failure. They selected seed corn from full, plump ears and saved only the larger uniform kernels from the center of the cob.

The corn types used by the Hidatsa included hard and soft white, hard and soft yellow, gummy, blue, dark and light red, and pink top. The hard types of corn were flints, and the blue, light red, dark red, pink top types were flour corn (see Chapter 19). The hard and soft white corns were the most commonly raised. The Indians planted each type of corn in separate fields to avoid mixing of corn types because they recognized that windblown corn pollen could travel to adjacent fields, creating a mixture of corn types. We now recognize this to be the **xenia effect**, or the immediate effect of foreign pollen on seed development and characteristics.

The Hidatsa prepared many dishes from corn including a mush made from mixing corn, beans, and squash with bison fat, and boiled balls made of corn. In addition, whole ripe ears of soft white and yellow corn were parched over fires



FIGURE 1-8
A watcher's stage. This was a raised platform from which Native American watchers could frighten bird and deer pests away from their crops.

Redrawn from Wilson (1987).

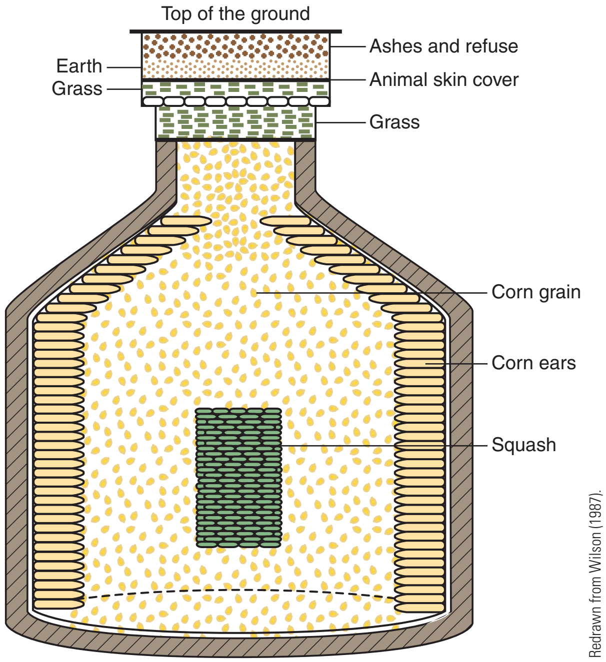


FIGURE 1-9
A winter storage cache. It was lined with grass and willow sticks. Some were as large as 2 feet (0.6 meter) at the mouth and 6–8 feet (1.8–2.4 meters) deep.

and eaten. The Hidatsa used both hard and soft, yellow and white corns to make into hominy (dried corn treated with lime to remove the hull from the kernels). Hominy is more nutritious than untreated corn.

Anasazi Agriculture

The Anasazi were agriculturally advanced Native Americans inhabiting the Southwestern United States, beginning roughly 11,000 to 10,000 years ago and peaking in 900 to 1130 CE. The region lies on the borders of Colorado, Utah, Arizona, and New Mexico. The temperature in the region is extreme and the seasonal rainfall is normally low but also unpredictable. Despite these limitations, the culture flourished. Hunting and gathering were the primary means of sustenance from 11,000 to 3500 years ago, until the introduction of corn from southern Mexico led to the development of an agriculturally based society. Corn was the leading crop, but squash and beans were also farmed. Cotton was also produced in areas with access to water. Turkeys were domesticated and used for ceremonial feathers, meat, and eggs.

The Anasazi farmed fertile land on flood plains near streams, but "dryland farming" without irrigation was not successful unless timely rains occurred. Crops were planted using digging sticks, and fields were cultivated using stone implements. Agriculture was supplemented by gathering wild plants including pinion nuts (pine nuts), acorns, yucca, prickly pear cactus, rodents, and deer. As agriculture advanced, the Anasazi irrigated their crops and developed and constructed canals and reservoirs for holding water.

About 900 CE, climatic changes leading to greater summer rainfall led to a dramatic increase in agricultural productivity and the golden age of Anasazi culture. During this period, construction of the great houses of Chaco Canyon occurred (Figure 1-10). The Anasazi had a knowledge of astronomy, and ceremonial centers were aligned with complex solar and lunar cycles. Crops were grown in a wide



FIGURE 1-10
Pueblo Bonito, the oldest part of the Chaco Canyon ruins, was built around 900 CE. This photo was taken in 1929.

geographic region and brought back to these spiritual centers to support social hierarchy, fuel the well-established trade networks for meat and luxury goods, and to store for insurance against future droughts. Remnants of their cities, including pithouses or pueblos, and cliff dwellings are studied by archeologists today. Like many early peoples, they painted or scratched images on the sandstone cliffs around their cities.

Two lengthy droughts around 1090 and 1130 CE, social unrest, and land degradation led to the disintegration of this society and widespread migration from these sites to mesa tops, river basins, and areas around the Southwest with more reliable access to water. However, the reasons for the Anasazi people's systematic abandonment of the great religious centers, and later cliff dwellings, remain a source of archeological debate. Today's Hopi, Zuni, Pueblo, and other Native American tribes are descendants of the ancient Anasazi people.

The Colonial Years of the United States

Many explorers traveled to the New World during the 1500s. The Spanish attempted to establish colonies in South America, Florida, and California. The permanent settlement of the 13 original colonies of the United States began in 1607 with the founding of Virginia and was concluded in 1732 with Georgia. In 1630, there were about 5000 colonists. But by 1750, the population had grown to more than a million. People came to the Americas for various reasons. Some were motivated by greed and came in search of gold and quick wealth. Others came for adventure, to escape religious persecution, or to gain freedom. Still others came to acquire land that was unavailable to the average person in England. Whatever the initial intent, most colonists became engaged in agriculture. To survive, they also practiced hunting and gathering.

Europeans came to a land that already had residents who had been living there for thousands of years. Native Americans lived in permanent villages and successfully practiced agriculture as well as hunting and fishing. The Native Americans were civilized, had leaders, played games, and were artists, but their culture differed greatly from that of the Europeans. The relationship between the two groups was sometimes harmonious and beneficial for both parties.

Lewis and Clark Expedition (1804–1806)

Meriwether Lewis and William Clark and their Corps of Discovery were commissioned by Thomas Jefferson to explore the lands obtained by the Louisiana Purchase and to seek a water route to the Pacific. Their journey up the Missouri River, across the Rocky Mountains, and down the Columbia River to the Pacific Ocean required unusual fortitude, stamina, and courage. They collected information on natural resources of the lands they crossed, documented soils and minerals, and discovered native plants and animals. Jefferson also wanted Lewis and Clark to interact with the Native Americans to establish potential trading relationships. Lewis and Clark spent the winter of 1804–1805 on the Missouri River in present-day North Dakota. Their log fort, Fort Mandan, was near villages of the Mandan and Hidatsa. The support of these Native Americans was critical for the survival of the expedition during its first year. During the brutally cold winter, the explorers were unable to obtain enough food from hunting and depended on corn obtained by trade with the Native Americans. Also, it was there they first met Sacagawea, a Shoshone, who had been captured in a raid by the Hidatsa. She provided invaluable help as a guide and translator on their journey to the Pacific.

Europeans gained knowledge of crops and production practices, and the Native Americans gained access to livestock, metal goods, and guns. Ultimately, the colonists exploited the Native Americans and appropriated the land they needed to expand their agriculture.

The original colonists struggled for survival in the new land. Most of the land on the east coast was forested. Therefore, trees had to be cut, land cleared, and stumps removed before any agriculture could occur. This took considerable time and energy. Accidents or illness could result in the loss of a season's harvest. Therefore, as a result of starvation, disease, and hostile interactions with natives, the colonist survival rate was usually less than 50 percent. Colonization succeeded by the continued immigration of new people. Many had little knowledge of agriculture; if they did, it was related to the crops they had cultivated in England. These crops often did not grow well in the soils and climates of the New World. The following is a brief description of two historical colonies.

The Virginia Colony

The Virginia Colony was settled in 1607 on the James River near the Atlantic Ocean entrance to the Chesapeake Bay. It later became Jamestown, named after King James I. The London Company financed the settlement, selling stock and hoping to generate profits from gold and other riches that might be found there. Unfortunately, the land they selected was marshy and without a reliable fresh water supply. Because of famine, contaminated water, and diseases such as dysentery and

typhoid fever, only about 20 percent of the original 104 colonists survived. The early colony survived only through replacement of colonists with new convoys, and it was not until 1620 that the Virginia Colony was sustainable.

The Virginia Colony was founded on land controlled by about 15,000 Woodland Native Americans who spoke Algonquian. These Native Americans survived through farming, hunting, and fishing of the rich tidal waters of the Chesapeake Bay. The colonists traded with or stole seed from these natives and learned to grow corn, squash, and beans. To expand agriculture to meet their food needs, the colony also had to appropriate lands used by the native people. Later, the colonists grew tobacco, which became the most important export to Europe. However, tobacco production depleted soil fertility and greatly reduced its productivity. Intensive tobacco production also increased the need for labor and contributed to the development of the slave trade. Later, colonists brought swine, cattle, and poultry. Free-roaming swine and cattle provided a source of meat for the colonists, but they also destroyed Native American crop fields.

The Plymouth Colony

In December 1620, the *Mayflower* anchored in Cape Cod Harbor. About half of the passengers were Pilgrims, who were religious separatists. Also on board were adventurers, indentured servants, and convicts. They had originally planned to settle in Virginia, but stopped short of their destination because of lack of food. Unlike the Virginia Colony, the Plymouth Colony (named after their port of departure) was established in an area where the Native Americans, the Wampanoag Indians, had been decimated by smallpox that French traders and fishermen introduced. Fields were already cleared of forests for planting. Unfortunately, as they say, timing is everything, and the December arrival followed by a cold winter resulted in the deaths of nearly half of the colonists.

The Native Americans Samoset and Squanto befriended the colonists the following spring and taught them skills for survival in the new land. Squanto taught them how to grow corn, beans, and squash and how to fish. In the fall of 1621, the colonists and Native Americans came together to celebrate their first harvest—the origin of our Thanksgiving holiday. At this holiday, the celebrants consumed the crops the colonists had grown as well as fish, venison, and berries. Although the colonists of the Plymouth Colony would suffer food shortages and continue to struggle for several more years, they would ultimately prosper. Their experiences would be repeated by other English colonists such as the Puritans (Massachusetts Bay Colony in 1629), who sought freedom in the New World.

Crops of the Colonies

Though the colonists grew indigenous crops, such as corn, beans, and squash, they also introduced other food crops and animals beginning in the early 1600s. The following are examples of crops introduced by the colonists:

- Cotton was grown commercially in Virginia in the early 1600s. It became the most important cash crop in the South, replacing tobacco in the 1800s. Slavery supported its production.
- Grains (wheat, barley, rye, and oat) were brought to North America by the Pilgrims and subsequent immigrants. The middle colonies of Pennsylvania, New Jersey, and New York became known as the breadbasket of the colonies.

Wheat was the most important crop in the colonies and was consumed locally and exported.

- Tobacco became the preeminent crop of commerce in Virginia, Maryland, and North Carolina. By 1775, the colonists exported nearly 100 million pounds (45 million kilograms) to England and Europe, where the populace had become addicted to the crop. They also grew tobacco in Connecticut. Because of its high labor requirement, tobacco production was a major factor in promoting slavery in the southern colonies.
- Rice was a very important crop in South Carolina and Georgia. By 1726, about 10 million pounds (4.5 million kilograms) were exported. Rice was typically produced on large plantations using slave labor.
- Indigo was an important export crop used as a blue dye. Europeans introduced it into South Carolina in 1740.
- Forage grass and legumes were likely introduced as seed in the feed of animals or as contaminants in ship ballast. White clover was widely distributed by the early 1700s and was known to the Native Americans as white man's clover. Alfalfa was first introduced into Georgia in 1736. Because early pastures were not widely cultivated, improved species were not purposely introduced. Much of the livestock at that time was not confined and roamed the landscape consuming whatever was available.
- Cows, beef cattle, sheep, and goats, first introduced into New England soon after the original colony was founded, were important livestock species. The New England region became a center for cattle and hog production, although livestock eventually became distributed throughout the colonies.

Evolution of Agriculture in the United States

For nearly the first 200 years following the settlement of North America by Europeans, farming for many was often labor-intensive **subsistence agriculture**, where crops and livestock were raised for the use of the farmer's family with little to spare. However, with mechanization, profitable commercial production was possible. Following is a brief review of some aspects of the mechanical and technological developments that influenced the development of American agriculture.

1600s–1700s: Manual and Animal Labor

With the beginning of colonization, hand labor was the primary approach to farming. The primary tools were the ax for tree cutting, the hoe and shovel for tillage and weed control, and the sickle and scythe for harvesting forage and grain (Figure 1-11). The grain cradle was a later invention that modified the scythe to gather stalks of grain (Figure 1-12). If oxen or horses were available, farmers could also use wooden plows and log or A-frame harrows for secondary tillage.

The typical wheat or oat grain production system colonists used was very labor intensive and consisted of the following steps: (1) Cutting the ripe grain with a sickle, scythe, or grain cradle; (2) manually bundling the grain and piling the bundles or sheaves into shocks; (3) loading the bundles onto a wagon for transport to the barn or threshing area; (4) threshing with a leather/wooden flail or treading the grain from grain heads by horses or oxen; and (5) separating the grain from the straw by winnowing (the process of separating the grain and straw fractions

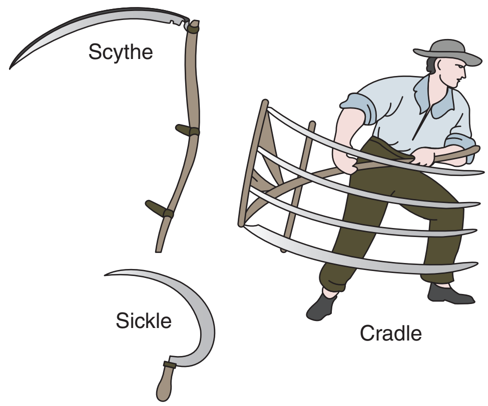


FIGURE 1-11
The sickle was developed by the Egyptians and used for thousands of years for grain and forage harvest. The scythe and grain cradle were later developments and were commonly used until the 1800s.



FIGURE 1-12
Cutting of wheat with a grain cradle.

by throwing the combined mixture into the air). The grain could then be fed to livestock, consumed by the family, or sold. Farmers often used oats for horse or oxen food. They frequently used the straw of oat or wheat for livestock bedding.

1800s: Mechanical Improvements

During this period, new mechanical inventions were developed for all phases of crop production. However, for most of this century, equipment was still horse- or mule-powered (Figure 1-13). After the Civil War, farmers made greater use of steam-powered engines. Newly developed plows made of cast iron and with steel shares and interchangeable parts were essential to break the tall grass prairies in the west. Inventors also developed improved harrows, grain planters, and cultivators.

Producers began using mechanical grain reapers (harvesters) and combines (reaping and threshing by a single machine), which were developed in the





University of Minnesota, Agricultural Experiment Station.

FIGURE 1-13
Teams of horses pulling disk harrows in preparation for seeding.

beginning to the middle of the 1800s (Figure 1-14). These machines vastly reduced the labor requirements of grain harvesting and greatly increased grain production.

Other advancements included the determination of the essential elements required in plant nutrition, and the development of the first mixed commercial fertilizers used to meet the nutrient needs of plants. In 1870, barbed wire was invented. This was a critical development for settlers on the range because it enabled fencing of rangeland and exclusion of free-ranging cattle.

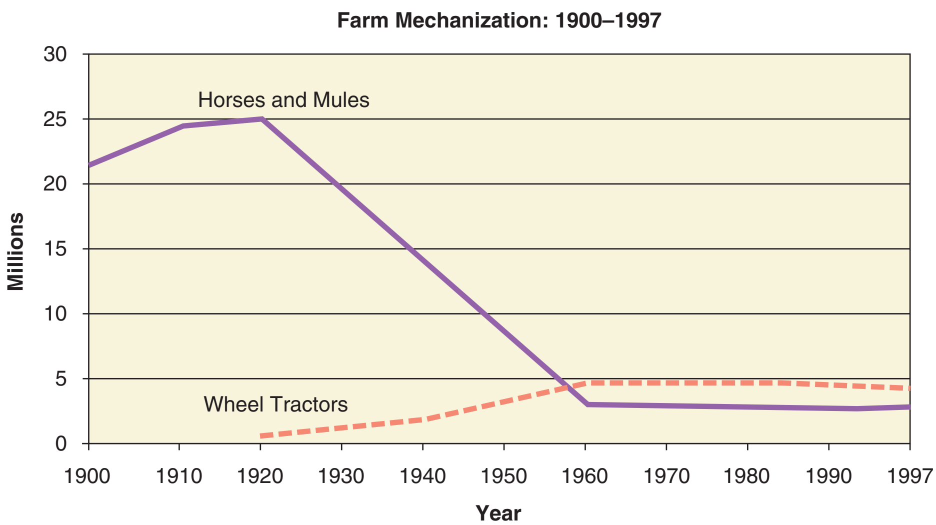
1900s–2000s: The Technology Revolution

From 1900 until 2000, greater changes occurred in agriculture than during all other times in history as people applied technology to agriculture. By the end of the 1900s, technology enabled most farmers to operate independently from their neighbors. The use of mechanical power, synthetic chemical fertilizers, pesticides, and herbicides became commonplace; human labor and animal power were replaced. In 1900, more than 20 million horses and mules were used for agriculture production, but by 1950, most of this livestock had been replaced by mechanical tractors (Figure 1-15).



University of Minnesota, Agricultural Experiment Station.

FIGURE 1-14
A grain binder cut and bound grain into shocks (above). The bundles of grain (below) were then picked up into piles before transporting to the threshing site.



Adapted from USDA-NASS (2007).

FIGURE 1-15
Mechanization by steam followed by gasoline engines replaced animal power in agriculture.

In the early 1900s, tractors and grain combines began to be powered by steam, although farmers did still use horses and mules. Because of the cost, individual farmers seldom owned steam engines. Custom operators often owned steam equipment and provided a service for hire (Figure 1-16). Usually a crew of workers or neighbors gathered at harvest time and moved from farm to farm, sharing labor.



Minnesota Historical Society.

FIGURE 1-16 Threshing machine connected to a belt driven by a steam-powered tractor. Bundles of grain collected from the field were fed into the threshing machine that separated the grain from the straw that is blown into stacks. This type of grain harvest was labor-intensive and required neighboring farmers to work together.





University of Minnesota, Agricultural Experiment Station and USDA.

FIGURE 1-17 In addition to tractors (left), other mechanization such as small grain and corn harvesters (right) improved the productivity of farming and reduced labor input.

The internal combustion gasoline engine, initially developed in the late 1800s, replaced the large steam engines (Figure 1-17). By the 1920s, low-priced farm tractors were commonplace. In addition to tractors, it became common for trucks and automobiles to move farm products, supplies, and people.

For the first half of the 1900s, small, diversified farms were prevalent. Hay and silage were important for feeding farm animals (Figure 1-18). For the forage farmer, mechanical advancements included the refinement of ensiling systems and development of hay baling systems with bales of variable size. However, even today, haymaking and storage are still labor-intensive agricultural operations.

Chemical inputs into agriculture became commonplace following World War II, in the mid-1900s. Inexpensive anhydrous ammonia and urea became widely

The Family Farm and Changing Works

In *Changing Works*, Douglas Harper (2001) describes the cheesemaking farm of the mid-1880s in upstate New York as a model of the sustainable family farm that prospered economically and socially and was the foundation of a viable rural community. The farms had a balance of resources, animals, crops and labor, but not many purchased inputs. Cheese was sold off-farm for cash. The farms were about 115 acres (47 hectares), had about 20 cows, two to five horses for farm work, and hogs, sheep, and poultry for on-farm consumption. Large gardens provided vegetables for the family. The farms grew a diversity of crops including wheat, oat, buckwheat, corn, potatoes, peas, and hay. Farmers used manure from livestock and green manures (see Chapter 5) from clovers for fertilizer. The farms produced as many calories as were expended on production. The family and "changing work" with neighbors provided labor. Changing works is the reciprocal sharing of labor and machinery among farmers to complete an important labor-intensive task such as haymaking or grain threshing. It was important for sustaining individual farms and for maintaining the rural community. Working and eating together brought the community together.



Minnesota Historical Society.

FIGURE 1-18
Haying on the Zimmerman farm, Marathon County, Wisconsin, using a mechanical hay lifter to lift hay from the windrow to the wagon. Historically, hay making and other farm operations were very labor intensive.

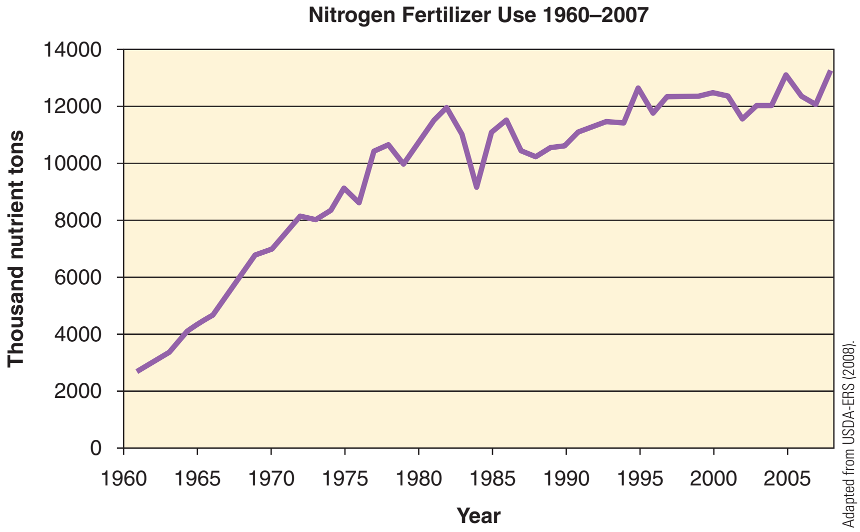


FIGURE 1-19
Use of nitrogen fertilizers from 1960–2007. Most nitrogen fertilizers are synthetic. One thousand tons equal 907 metric tons.

used nitrogen fertilizer sources for grain crops due to the development of the industrial production of synthetic ammonia fertilizers (Figure 1-19). Widely available, inexpensive chemical fertilizers were important for increasing the yield potential of grain crops. Before chemical fertilizers, animal manures or legume green manures were the primary resources for renewing soil fertility. Animal manures necessitated the production of livestock and their feeds, and manures often contained inadequate levels of all nutrients necessary for profitable crop production. Legume green manures could supply the nitrogen fertilizer needs of grain crops but required diversion of land for their production.

Chemical herbicides replaced hand weeding and cultivation for weed control. This greatly expanded production because acreage of corn and other row crops had been limited by the time required for weed control. Also, the space between crop rows had to be wide enough to allow passage of horses or tractor tires. The first widely used herbicide was 2,4-dichlorophenoxyacetic acid (2,4-D). It injured or killed many broadleaf weeds in corn and wheat crops without affecting the corn and wheat. Later, beginning in the 1950s, many additional herbicides were developed and introduced, such as, atrazine, treflan, and glyphosate. Chemical compounds, such as insecticides and fungicides, were also developed to fight other crop pests that reduced crop yields.

The 1900s also saw major improvement in crop varieties through plant breeding and genetics. Crop yield potential has greatly increased through selection for disease resistance and tolerance to environmental stress. Crop traits such as grain uniformity and nutrient concentration have also been altered. A striking example of successful plant breeding is the development of hybrid corn in the early to mid-1900s that resulted in significant yield increases compared to traditional open-pollinated varieties. In the late 1900s, an understanding of plant genetics led to the development of genetically modified crops with special traits such as herbicide resistance and insect resistance. One example is Bt (*Bacillus thuringiensis*) corn and cotton. Genes are taken from *Bacillus thuringiensis*, a soil bacteria, and are inserted into these crops to protect them from some insects; the use of Bt cultivars can actually reduce the need for insecticide use.

Another important development of the late 1900s was precision agriculture. **Precision agriculture** is the use of technology, including Global Positioning

System (GPS) and yield monitors, to record site-specific data to aid in management decisions. Fields are naturally variable spaces and these new techniques provide variable amendment recommendations tailored to individual areas within sites, rather than using a single application rate for an entire field. Originally, the technology was first put into practice for improving fertilizer or manure application, but has been expanded to optimize pest detection and pesticide application, tillage, planting, harvesting, and irrigation. Some of the benefits of precision agriculture are better crop quality, increased sustainability, and greater protection of natural soil and water resources.

Farm Productivity

Mechanical and technological advances combined with improved management have increased the efficiency of agriculture. In economic terms, this has resulted in more output (production of grain, meat, and so on) as overall input (land, labor, fertilizer, and seed) has remained the same or decreased (Figures 1-20 and 1-21).

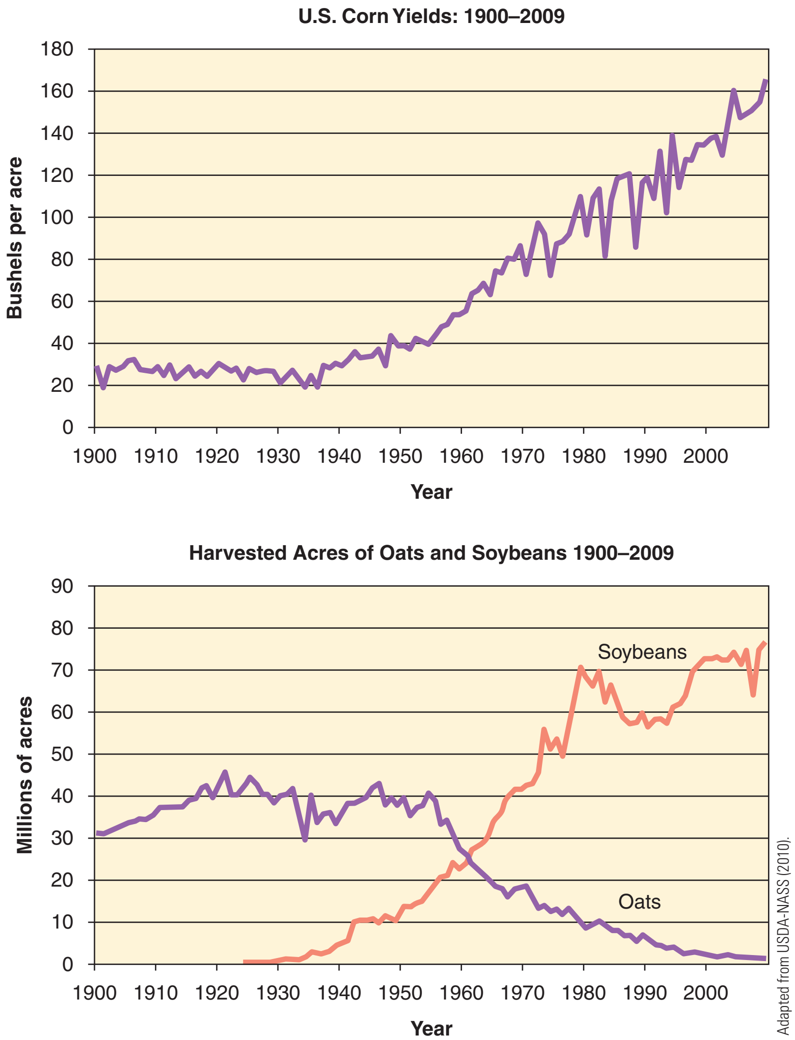


FIGURE 1-20
Corn yield changes were due to development of the hybridization process and improved management such as the use of nitrogen fertilizers and herbicides. During this period, soybeans emerged as a major crop through development of markets, new varieties, and management. Oat acreage declined in large part because of fewer horses and mules that used oats as a feed source. One bushel/acre of corn equals about 63 kilograms/hectare. One million acres equal 404,711 hectares.

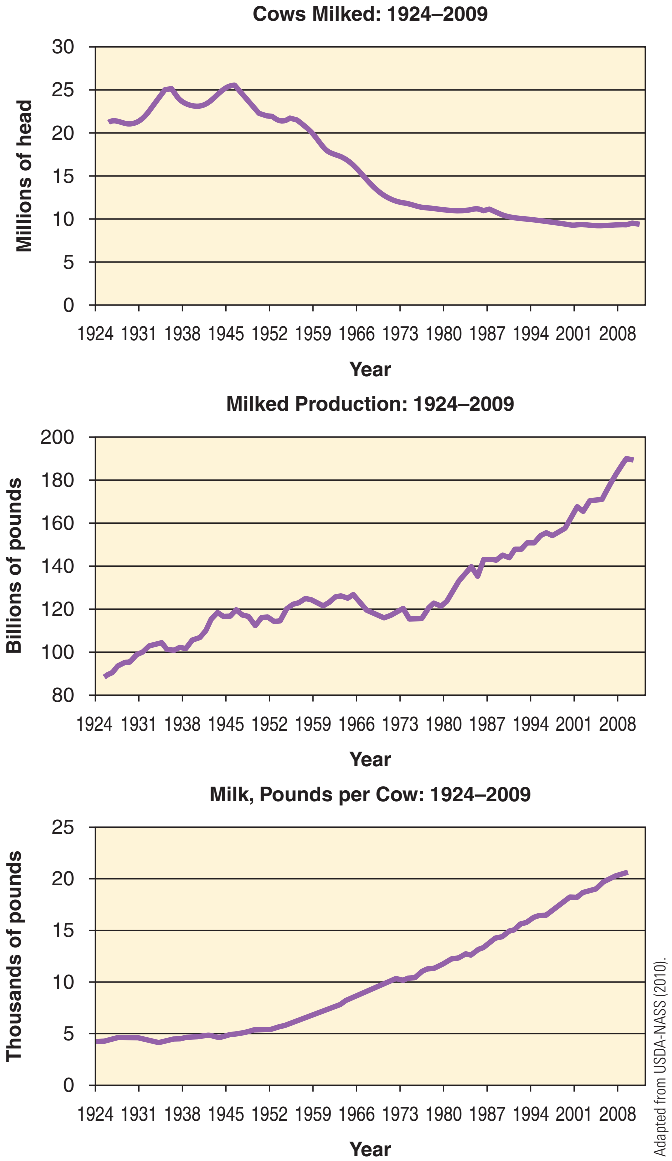


FIGURE 1-21 While the number of milked cows has decreased over time, milk production per cow and total milk production has increased. These changes are related to improved breeding, feeding, and management of animals. One billion pounds equal about 45 million kilograms. One thousand pounds equal 454 kilograms.

Agricultural productivity has increased nearly 1.8 percent per year since 1950 (Figure 1-22). Efficiency in productivity has resulted in abundant food sources that enable North American consumers to spend a smaller proportion of their income on food than do people on any other continent (see Chapter 2). A significant crop and meat export market to foreign countries has also developed.

Numbers of Farms and Farmers

The number of farms, which peaked at more than six million in the 1920s, has declined more than 60 percent (Figure 1-23). The number of farmers has also dramatically declined, and today only about 1 percent of the total population is engaged in farming (Figure 1-24). Mechanization and technology reduced the

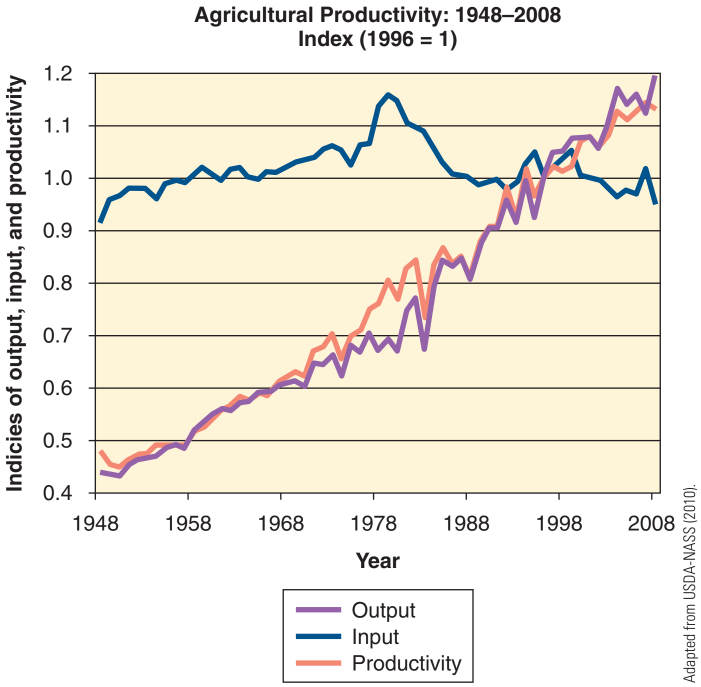


FIGURE 1-22
Agricultural productivity has increased significantly over the past 50 years, whereas input costs have decreased. Input costs are the costs of production including seed, fertilizer, equipment, and labor.

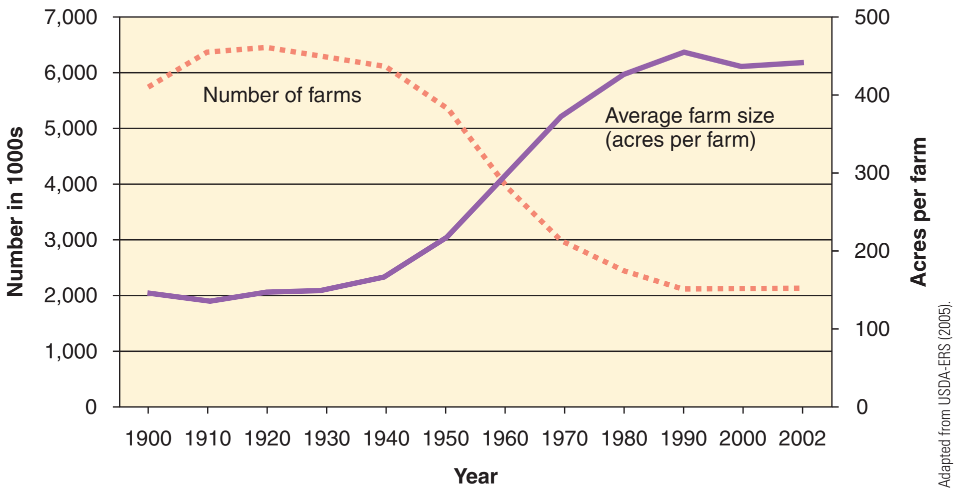


FIGURE 1-23
Number of farms and average farm size from 1900 to 2002. As the number of farms has declined, their average size has increased. One acre equals 0.4 hectare.

labor requirement needed on the farm. In addition, many who once farmed for subsistence have left farming for more lucrative employment opportunities in cities. The children of farmers who did not have access to land or capital to begin farming also departed for other occupations.

The size of farms has increased and farms have become much less tdiversified. These changes increased the efficiency of production and marketing. Larger acreages were required to pay for equipment and technology costs. Economies of scale can be realized by becoming larger (Figures 1-25, 1-26, and 1-27). This allows for increased specialization of management and resources.

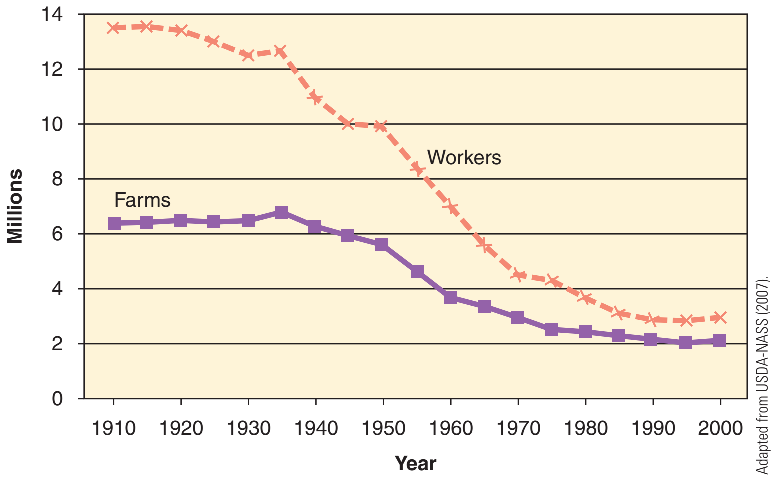


FIGURE 1-24
Number of farms in the United States and all farm workers from 1910 to 2000. The number of farm workers has decreased over time because of the increase in labor-saving technology and the decrease in overall number of farms.

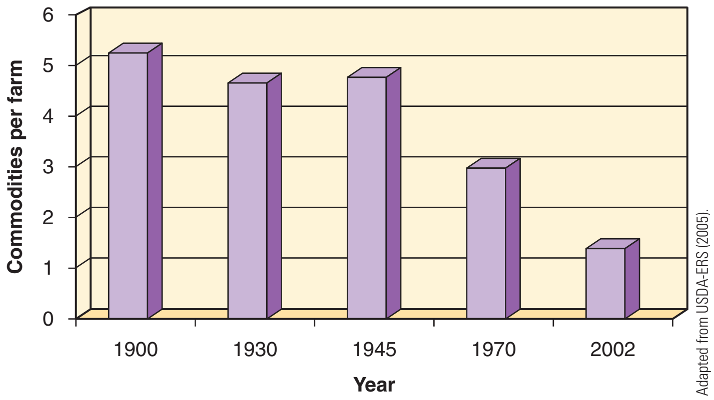
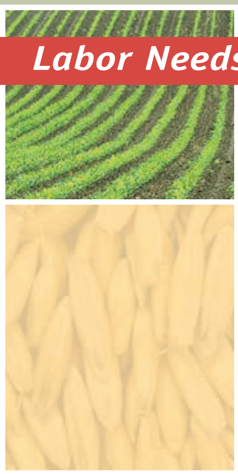


FIGURE 1-25
The number of commodities produced per farm from 1900 to 2002. As farms have become more specialized, the number of commodities has decreased.



Labor Needs for Wheat Production

- In 1830, about 275 hours of labor produced 100 bushels (2722 kilograms) of wheat on 5 acres (2 hectares).
- In 1890, about 45 hours of labor produced 100 bushels of wheat on 5 acres.
- In 1930, 15 hours of labor produced 100 bushels of wheat on 5 acres.
- In 1975, between 3 and 4 hours of labor produced 100 bushels of wheat on 3 acres (1.2 hectares).
- In 2000, 2 hours of labor produced 100 bushels of wheat on 3 acres.

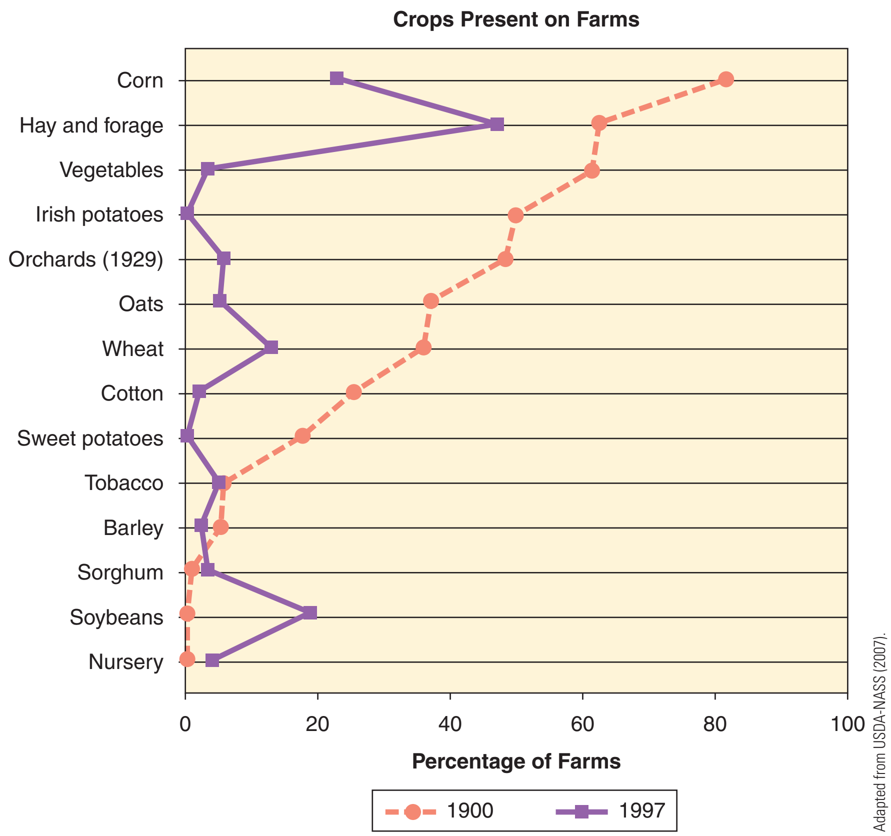


FIGURE 1-26
A comparison of crops present on farms in the years 1900 and 1997.

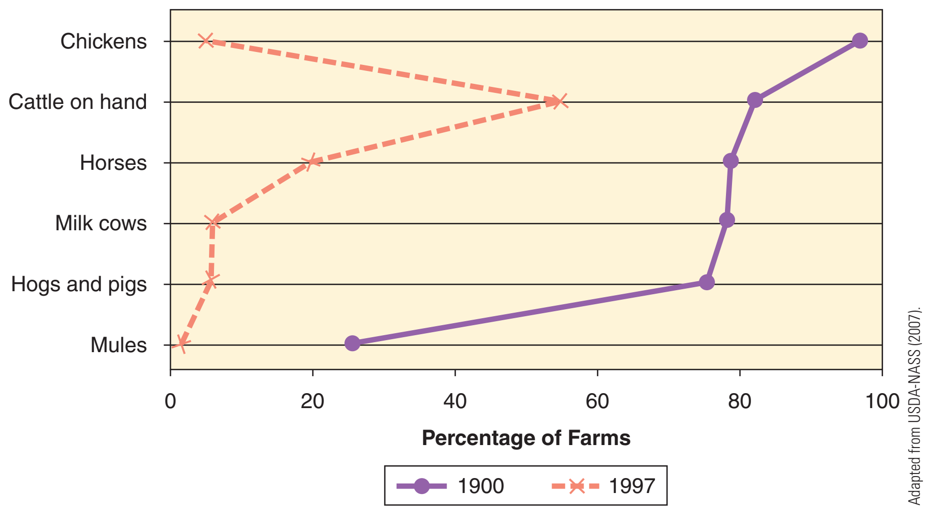


FIGURE 1-27 Livestock present on farms. Changes during the twentieth century in the percentage of farms with a diversity of crop and livestock. For example, in 1900, nearly 80 percent of farms grew corn and raised small flocks of chickens. By the end of the century, 20 percent of farms grew corn, and chickens were raised on about 5 percent of the farms.

Land Policy

The land has always been a unique resource that the United States has possessed. From colonization until the 1900s, the federal government distributed more than a billion acres (400 million hectares) of public lands. This land distribution was controversial. Some leaders, such as Thomas Jefferson, who followed the agrarianism philosophy (see next section), felt that land should be distributed to create a democratic nation of small farmers. Others thought land should be sold to generate tax revenue. Some pioneers sought land for agriculture, but many businesses, bankers, and farmers were interested in land speculation, that is, buying and selling land for profit.

Legislation was passed beginning in the late 1700s to provide for the distribution of unsettled land. The most significant legislation was the **Homestead Act of 1862**. It provided a United States citizen who was 21 years or older the right to claim 160 acres (65 hectares) of public land. The homesteader had to live on the land for five years and make improvements. This act provided for the settlement of the Great Plains. The federal government also made land grants of more than 130 million acres (53 million hectares) to railroads to help them finance the construction of new rail lines. This land was often sold to farmers to produce grain or livestock, which was shipped on the railroads.

Agrarianism and the Family Farm

Agrarianism is the belief that farming is the best way of life and the most important economic endeavor. At one time in the history of North America, farming was the primary occupation. Food production was the most fundamental activity for survival. The idea of agrarianism was important to the ancient Greeks, who felt that the family farm and farmers were the foundation for their society. Later, Thomas Jefferson considered the small farmer to be the bastion of freedom and democracy. When he made the Louisiana Purchase in 1804, it was in part to provide land for agricultural expansion. In agrarianism, farming is the most important economic activity, and living in rural areas is socially and morally superior to living in the city. Today, though we recognize the importance of food production, we recognize that many occupations contribute to our society and our economic prosperity.

Review Questions

1. How did the food production techniques of the earliest Native Americans differ from those of the first European settlers to come to North America?
2. What type of knowledge did the Native Americans acquire as they developed their food production techniques?
3. When were crops first domesticated, and what are some of the reasons for crop domestication?
4. Identify several locations worldwide where crops were domesticated.
5. Discuss which crops were dominant in early civilizations. Focus on the Fertile Crescent, East Asia, Central America, and eastern North America.

6. What are some of the ways in which crops were moved from one region to another?
7. Discuss the agricultural traditions of the Hidatsa people of North America.
8. How did the agriculture of the Anasazi differ from the Hidatsa?
9. What was the Columbian Exchange?
10. What made life so difficult for early European colonists, and who helped them learn to survive?
11. What were some of the most common crops grown in the new colonies?
12. What caused the increase in the use of slave labor in the new colonies?
13. How has agriculture been able to evolve so rapidly and on such a large scale?
14. Describe the technological changes that occurred in the twentieth century that greatly increased agricultural productivity.
15. Discuss some of the most important U.S. government policies that have affected the development of agriculture.

Critical Thinking

1. Throughout this chapter, we have discussed how agriculture has evolved throughout the world, and we have specifically examined some very specific geographic regions. Research and write a short essay on the agricultural history of your family or your home town, or the region in which you are currently living.
2. Consider how Native Americans originally used the land in your state or region and how use of the land has changed over time.
3. It has been 400 years since the settlement of Jamestown, and archeological studies have revealed much about the struggles of the colonists. Review the lives of historic leaders, such as John Smith, John Rolfe, and Powhatan and discuss the contributions of each to the success of the colony.

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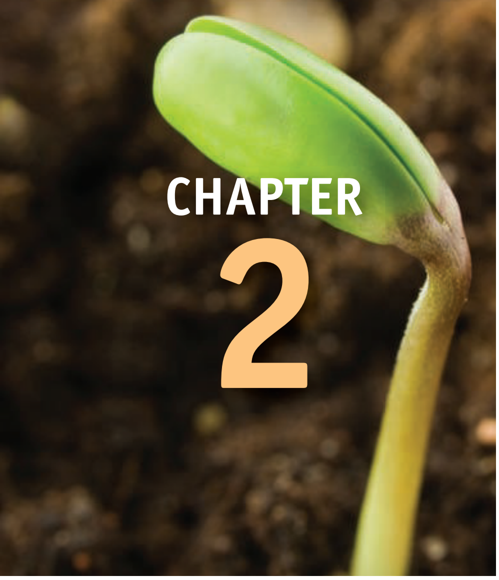
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CHAPTER 2



Agriculture Today





Key Concepts

- Farms can be defined by use, stewardship, or economics.
- Those involved in farming come from a variety of backgrounds and economic status.
- Farming is critical to our national security and to our economy.
- The United States Department of Agriculture (USDA) is the government agency that represents agricultural interests.
- The federal farm policy is legislation designed to support agriculture and reduce the risks.

Key Terms

acre
agribusiness
agricultural export
agricultural import
commodity payment
conservation payment
Conservation Reserve Program (CRP)
disaster payment
farm
farm bill
gross domestic product (GDP)
hobby farm
section
United States Department of Agriculture (USDA)
vertical integration

Introduction

Agriculture provides many benefits to our society and our environment. It produces the food we eat and fiber for our clothing. Agriculture is now providing energy to power vehicles and heat our homes. Agriculture is a significant part of our national economy and provides many jobs directly for farmers and for others in the food and service industries. The food and fiber production system begins at the farm and proceeds through processors to the consumers.

Within the federal government, the **United States Department of Agriculture (USDA)** represents agricultural interests. The USDA provides leadership on food, agriculture, and natural resource issues. Its budget includes funding for food assistance, agricultural research, international trade, commodity support, and environmental conservation.

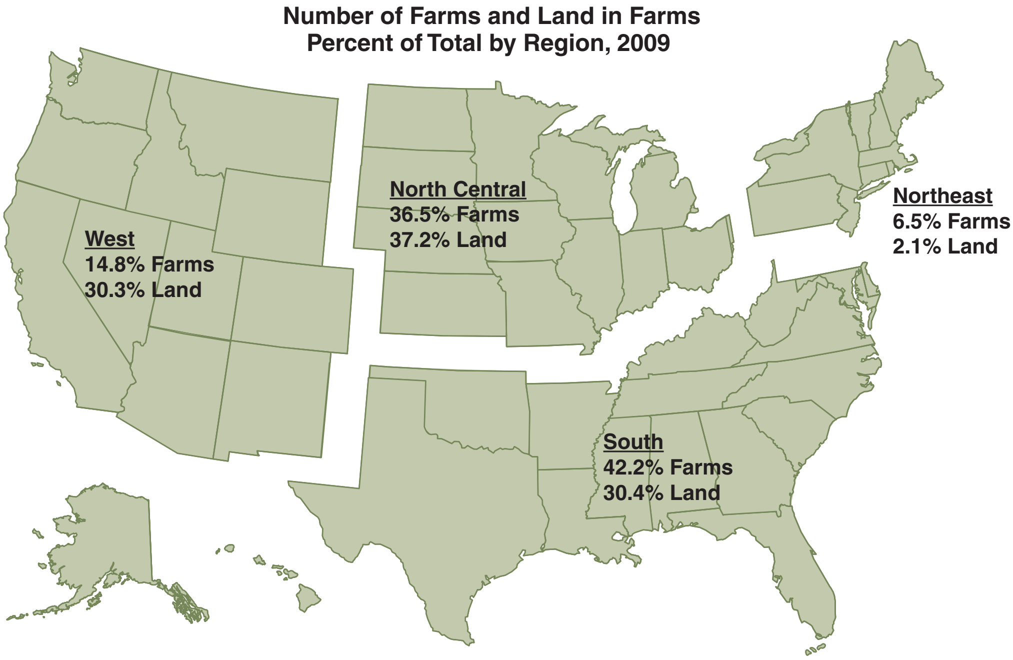
What Is a Farm?

Dictionaries define a **farm** as "a plot of land devoted to agriculture and to the raising of crops and domesticated animals." Farms are also places where humans live and practice stewardship of the land and nature (Figure 2-1). The USDA defines a farm based on economics: A farm is any place from which $1000 or more of agricultural products are sold annually. The United States has about 2.1 million farms with an average size of 444 acres or 180 hectares (Figures 2-2 and 2-3).



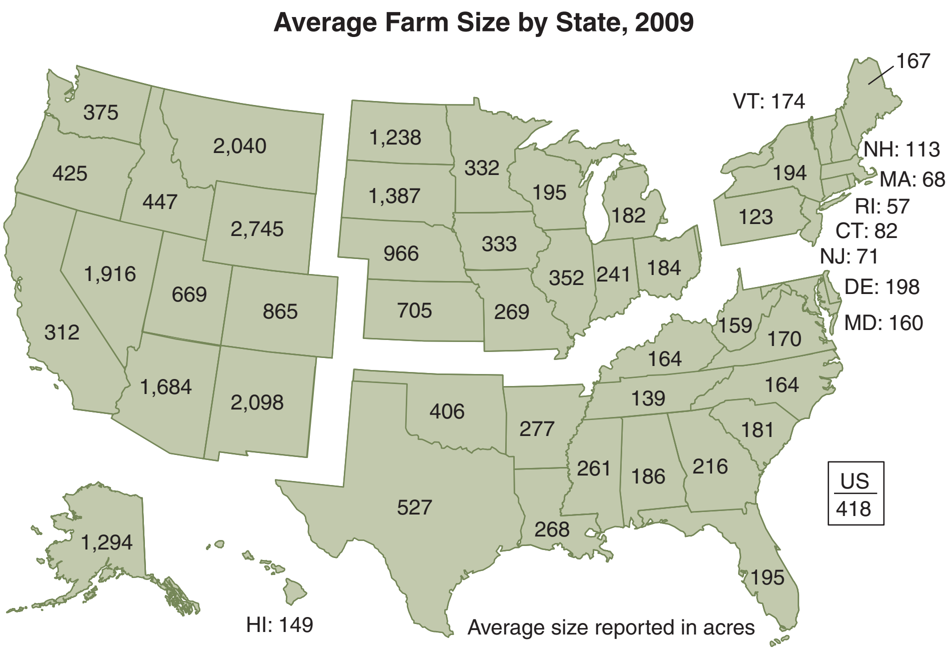
Ron Nichols, USDA.

FIGURE 2-1
A family dairy farm in Wisconsin.



Adapted from USDA-NASS (2010).

FIGURE 2-2
Average regional farm numbers and land in farms in 2009.



Adapted from USDA-NASS (2010).

FIGURE 2-3
Average farm size by state in acres in 2009. The average farm in the United States is 418 acres. 1 acre = 0.4 hectare.

Average farm numbers and farm size vary considerably among states. Farm numbers reflect a state's size and the relative importance of agriculture to a state's economy. Texas has the most farms, and New Jersey has the least. Average farm size reflects a state's crop production potential. For example, in North Dakota and Montana, low rainfall reduces crop yield, so a larger farm is required for profitability. In other states that have high rainfall and favorable growing conditions, less acreage is required for a profitable farm. In the eastern United States, high value horticultural or gardening crops that are very labor intensive are produced on many small farms.

The USDA has characterized farms by their level of sales (Table 2-1). More than 50 percent of the total farms in the United States are small farms with an average of 100 acres (40 hectares) and with less than $10,000 in annual farm sales. Many of these farms are considered to be **hobby farms** with a high dependence on off-farm income. Large farms with sales more than $500,000 have an average size of about 2,500 acres (1,151 hectares). Only about 4 percent of all farms are considered large farms, but these farms account for almost half of the total agricultural production in the United States (Table 2-2). They also have a higher profit margin than small farms. Very large farms produce a high proportion of hog, beef, poultry, and dairy products, as well as important field crops.

TABLE 2-1

Number of farms, land in farms, and average farm size by economic sales classes in the United States in 2009. Farms with income of <$10,000 are the most numerous but have the smallest amount of land. Farms with $500,000 or more in sales are the smallest category but have a significant amount of land. Larger farms have significantly greater sales than smaller farms. *Adapted from USDA-NASS (2010).*

	Number of farms	Land in farms	Average farm size
Economic sales class	Percentage of total (%)		in acres
$1,000–$2,499	28	3.7	55
$2,500–$4,999	14.4	3.2	93
$5,000–$9,999	13.4	4.6	143
$10,000–$24,999	11.8	6.5	230
$25,000–$49,999	8	7.8	408
$50,000–$99,999	7.4	10.4	588
$100,000–$249,999	6.8	16.1	991
$250,000–$499,999	4.5	16.2	1,506
$500,000–$999,999	3.4	15.4	1,895
$1,000,000 +	2.3	16.1	2,936

TABLE 2-2

Agriculture production for the five farm sales classes in the United States. *Adapted from USDA-ERS (2006b).*

Annual sales (2002 dollars)

	Share of production (%)	
Economic sales class	**1989**	**2002**
<$10,000	2.4	1.9
$10,000–$99,999	21.3	11.9
$100,000–$249,999	22.2	17.0
$250,000–$499,999	19.0	16.8
>$500,000	28.9	43.9



Land Measurement

In American agriculture, land area is measured as **acres** and **sections**. One U.S. survey acre is a land area of 43,560 square feet or 4840 square yards (4047 square meters). Farm size, crop yields, and fertilizer rates are often expressed on a per acre basis. Early English colonists brought the term *acre* to the Americas. The concept was originally used in the thirteenth century during the reign of Edward I in England. An acre was the amount of land a man and a team of oxen could till in one day. Because of the challenge of turning a team of oxen, an acre was originally designated as 66 feet (20.1 meters) wide by 660 feet (201.2 meters) long. The term furlong was derived from the two words: furrow and long feet. A furlong was the distance (660 feet) a team of oxen could pull a plow without stopping. An acre may be any shape but must equal 43,560 square feet (4047 square meters). In the metric system, land is measured in hectares rather than acres. Most suburban house lots are less than one acre.

A section describes a land area of 1 square mile (2.6 square kilometers) or 640 acres (259 hectares). In the late 1700s when the United States was still largely unsettled, Congress passed the Northwest Ordinance of 1784. This law provided for the survey and legal identification of all new lands open to settlement. With this system, land was divided into a grid of squares with boundaries running north to south and east to west. The largest unit was a township, a 6-mile by 6-mile (9.7 kilometers by 9.7 kilometers) square. Each township was divided into 36 sections, each 1 mile by 1 mile (1.6 kilometers by 1.6 kilometers) square. Townships can be identified by a designation such as T7NR2W, which consists of its township number that denotes its location north or south, and range number

(*Continued*)

that denotes its location east or west. For homesteading, sections were divided into quarters of 160 acres (67.4 hectares). Families that lived on and improved the 160-acre quarter section gained title of the land. Today, in many regions, a quarter section of land is too small to support a modern farm without off-farm income.

Farmers

About 1 percent of the U.S. population is directly involved in farming. Most farms in the United States (98%) are family farms. Because of the business nature of farming today, many family farms with significant agricultural sales are organized into partnerships or family corporations.

Farmers can be of any race, gender, or age. The U.S. census of 2007 showed about 56,000 farm operators to be of Hispanic or Latino origin and about 31,000 of African American origin. Hispanic migrant workers also make up a significant percentage of agricultural laborers throughout the United States. Women are the primary operators of many farms. Many other women, in their role as spouses to farmers, have a significant and often unrecognized role in farming.

Farming Income

The average farm household income for the United States was about $90,000 in 2007. However, there is a considerable range in income levels and also in the sources of that income (Table 2-3). Farmers benefit from having diverse income streams, that is, having income from several sources in addition to the sale of farm products. These income sources include off-farm employment (93% of farm households have off-farm income), government financial support, and other business ventures. Although small farms may have operating losses from farming, these households do have other sources of income to offset the farming losses.

Financial Support

Farmers received more than $160 billion from 1995 to 2005 in financial support from the USDA (see USDA discussion at the end of this chapter). The USDA provides financial support to farmers for several reasons: to insure production of important food and fiber crops; to maintain low food prices; to promote soil and water resource conservation; and to maintain farmers when a natural disaster such as a drought or a storm strikes. The three types of financial support to farmers are commodity, conservation, and disaster payments (Figure 2-4).

TABLE 2-3

Average household income of farmers as well as outside sources of income in 2003. Farms in all sales classes depend on off-farm income. *Adapted from USDA-ERS (2004a).*

	Total on-farm income	Total off-farm income
Economic sales class	Income per household ($)	
$9,999 or less	–5,755	67,892
$10,000–$99,999	–1,365	55,638
$100,000–$249,999	25,321	33,949
$250,000–$499,999	37,182	33,011
$500,000–$999,999	87,994	30,825
$1,000,000 or more	332,494	34,731

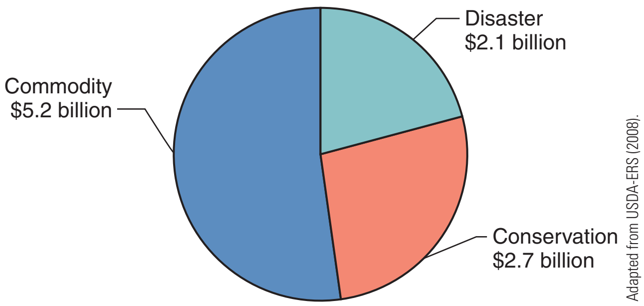


FIGURE 2-4
2008 USDA payments to farmers for farm programs, conservation programs, and disaster programs. Farm programs are for commodity support; conservation programs include land retirement programs; and disaster programs include payments for drought or environmentally induced agricultural disasters.

Financial support in terms of direct payments and price supports, called **commodity payments**, have been provided for specific commodities including dairy, peanut, corn, barley, wheat, oat, rice, and soybean (Table 2-4). Corn production receives the largest subsidy. These payments have been controversial because some feel that farming should not be supported and because more than 50 percent of the commodity payments are made to the largest farms. Because support is often related to production of a specific crop, farms that produce higher volumes of these commodities naturally receive higher payments. **Disaster payments** are emergency payments to farmers when yields are low or nonexistent due to poor growing conditions. **Conservation payments** are for programs that aim to reduce the production of crops on environmentally sensitive lands (Table 2-5). The **Conservation Reserve Program (CRP)** and the Conservation Security Program are examples of two federally funded farm programs. To learn more about farm subsidies, see the USDA's web page at http://www.usda.gov/.

TABLE 2-4

The top 20 subsidies or payments provided to farmers as part of the U.S. government programs. *Adapted from Environmental Working Group (2010).*

Rank	Program	Number of recipients	Subsidy total
1	Corn subsidies	8,631	$3,975,606,299
2	Cotton subsidies	118,449	$2,270,123,381
3	Wheat subsidies	10,763	$2,232,477,345
4	Conservation Reserve Program	448,132	$1,866,558,139
5	Soybean subsidies	5,042	$1,727,643,051
6	Dairy Program subsidies	50,848	$1,148,283,594
7	Rice subsidies	611	$ 434,103,182
8	Sorghum subsidies	2,922	$ 270,141,110
9	Disaster payments	37,997	$ 243,838,571
10	Tobacco subsidies	59,575	$ 202,918,426
11	Livestock subsidies	24,994	$ 168,328,882
12	Barley subsidies	4,032	$ 107,689,567
13	Peanut subsidies	1,903	$ 101,808,869
14	Sunflower subsidies	231	$ 54,406,960
15	Canola subsidies	30	$ 21,807,319
16	Biomass	187	$ 10,387,114
17	Oat subsidies	1,478	$ 8,481,591
18	Wool subsidies	9,526	$ 6,493,338
19	Flax subsidies	22	$ 5,519,682
20	Safflower subsidies	107	$ 2,103,872

Land Use

Agriculture directly or indirectly uses more than 50 percent of land resources in the continental United States (Table 2-6). Of the land in all states, about 23 percent of the land is used for crop production; 31 percent is grazed cropland, permanent pasture, and range; and 30 percent is grazed forestland. The intensity of use and economic productivity of each category varies. Grazed forestland and rangeland are used less intensively than cropland.

The United States has about 440 million acres (178 million hectares) of cropland. About 75 percent of the cropland is used in production of mechanically

TABLE 2-5

Funding for major USDA conservation programs, 2002 to 2007. *Adapted from USDA-ERS (2008).*

Program focus/program	2002	2003	2004	2005	2006	2007
	$ million					
Land retirement programs						
Conservation Reserve Program	1,785	1,789	1,850	1,862	1,931	1,948
Wetlands Reserve Program	284	285	285	267	191	248
Working land programs						
Environmental Quality Incentives Program	390	691	903	950	992	993
Agricultural Water Enhancement Program	25	45	65	65	70	60
Conservation Security Program	0	0	41	202	257	382
Wildlife Habitat Incentives Program	15	29	38	46	43	42
Agricultural land preservation						
Farm and Ranch Lands Protection Program	51	98	91	112	74	73
Grassland Reserve Program	0	54	57	71	35	13
Conservation Technical Assistance	**679**	**712**	**742**	**696**	**687**	**627**
Total, major conservation programs	**3,229**	**3,703**	**4,072**	**4,271**	**4,280**	**4,386**

harvested crops such as corn, soybean, cotton, wheat, and alfalfa. About 10 percent of the land is planted as pastures with species such as smooth brome-grass and white clover. Another 10 percent of the cropland is classified as idle cropland. Some of this idled land in low rainfall regions is fallowed or not cropped to conserve moisture. Other idle land is part of government programs such as the Conservation Reserve Program (CRP) and Wetland Reserve Program (WRP). The Conservation Reserve Program (CRP) and Wetland Reserve Program (WRP) are U.S. government-funded programs that compensate eligible land-owners

TABLE 2-6

Major uses of land in the continental United States in 2002. One million acres equal 404,686 hectares. *Adapted from USDA-ERS (2006c).*

Land use	Million acres	Percentage of total (%)
Cropland (includes CRP)	441	23.3
Grassland pasture and range	584	30.8
Forest-use land	559	29.5
Special use (includes recreation/wildlife areas, farmsteads, and farm roads)	153	8.1
Urban	59	3.1
Miscellaneous	97	5.1
Total land area	1893	100

for participation. The Conservation Reserve Program was established by the Food Security Act of 1985 to remove erodible land from production by restoring perennial vegetation such as native prairie grasses and forests. Today, an environmental benefits index (EBI) that considers water quality, air quality, soil erodibility, and wildlife habitat is used to enroll land in the program. Contracts with landowners are typically 10 years in duration. The maximum enrollment has been about 35 million acres with a program cost of about $2 billion, but the 2008 Farm Bill limits the CRP acreage to 32 million acres. The CRP and other historic land retirement programs such as the Soil Bank Program during the 1950s and 1960s affect environmental quality, but they also impact commodity prices by taking land out of production.

Wetlands account for about 7 percent of the nonfederal land area in the continental United States. They are located within forests, and to a lesser extent within cropland. Wetlands provide vital ecosystem services on our landscapes including habitat for wildlife and plants, protection and improvement of water quality, sequestration of water to reduce flooding, and nutrient recycling and sequestration. The smaller Wetlands Reserve Program with an enrollment of less than two million acres was established by the Food, Agriculture, Conservation, and Trade Act of 1990. Funding provides for permanent restoration and improvement of wetlands, many of which are threatened by development and drainage. Currently, more than 31 million and two million acres (13 million and 810,000 hectares) are enrolled in the Conservation Reserve Program and Wetland Reserve Program, respectively (Figure 2-5).

Land use varies greatly throughout the United States (Table 2-7). It is affected by climate and potential for crop growth, topography, and economic development. The amount of cropland is greatest in the Midwest to the Southern Plains. The proportion of forestland and urban areas increases in the East. Grassland pasture and rangeland are greatest in the Southwest.

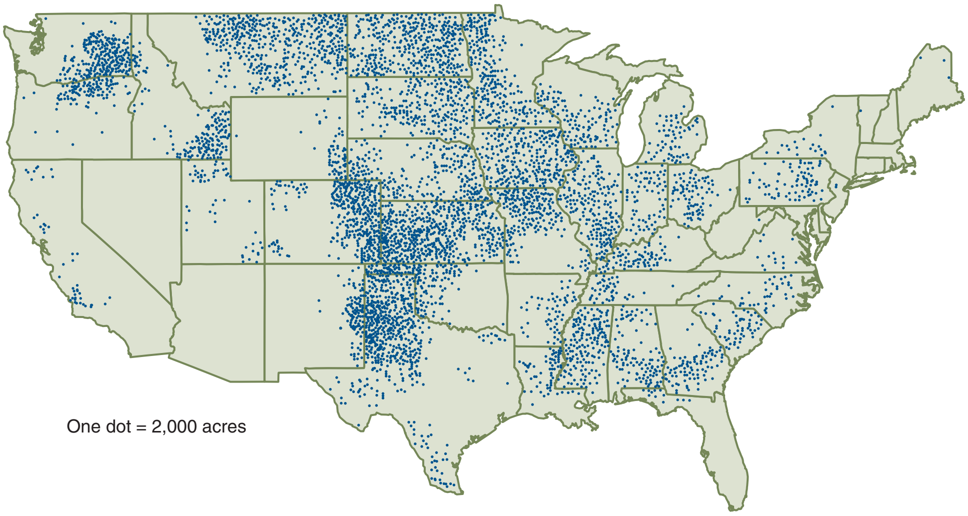


FIGURE 2-5
The distribution of CRP acreage in the United States in 2009. 1 dot = 2000 acres, or 809 hectares.

TABLE 2-7

Land use by percentage of total land in states within the United States by region in 2002. Cropland is land used for grain, fiber, or forage crops used in rotation or in cultivated summer fallow. Grassland pasture and range consists of open land used primarily for pasture and grazing. Forest-use land is used primarily for tree production. *Adapted from USDA-ERS (2006c).*

		Cropland	Grassland pasture & range	Forest-use land
Region	**States**		**% of total land**	
Northeast	ME, NH, VT, MA, RI, CT, NY, NJ, PA, DE, MD, DC	12.3	2.7	58.8
Lake States	MI, WI, MN	34.5	4.4	40.1
Corn Belt	OH, IN, IL, IA, MO	58.1	8.0	19.0
Northern Plains	ND, SD, NE, KS	52.5	36.5	2.2
Appalachian	VA, WV, NC, KT, TN	21.0	5.1	57.8
Southeast	SC, GA, FL, AL	12.0	6.7	59.8
Delta States	MS, AR, LA	23.0	6.8	55.6
Southern Plains	OK, TX	26.3	54.8	8.5
Mountain	MT, ID, WY, CO, NM, AZ, UT, NV	8.5	55.3	21.3
Pacific	WA, OR, CA	11.7	25.7	38.4
Far West	AK, HI	0.1	0.6	24.9



Land Capabilities Classification

The land capabilities classification is a system for identifying and categorizing nonfederal cropland throughout the United States. It was initially created to describe the suitability of lands and soils for crop production in response to a growing awareness of soil erosion during the early twentieth century. The classification system divides soil and landscapes into eight general categories, denoted by Roman numerals. Classes I through IV are suitable for crop production where classification depends upon where the landscape is located, slope, and fragility and depth of the soil. Classes V through VIII are not suitable for cropland but may be used for pasture, woodland, wildlife conservation, recreation, or beautification purposes. As the system has developed, subclasses within the main classes and additional clarifications further identify potential erosion dangers of land use throughout the United States. The land capabilities classification system can be used as a farm-planning tool and information from the farm scale to the county/state scale is readily available in soil surveys and on the Internet.

Most soil scientists today prefer the universal soil loss equation, which quantifies some of the same information in a numeric scale. For more information, visit the USDA-NRCS website at www.nrcs.usda.gov.

Crops

U.S. farmers grow more than 25 different primary crops. However, four crops—corn, soybean, wheat, and hay—are grown on more than 250 million acres (100 million hectares) or more than half of the cropland acres in the United States (Table 2-8). Ten crops including corn, soybean, hay, wheat, cotton, potato, sugar beet, rice, sorghum, and tobacco have a production value of more than $1 billion. There are nine other crops such as canola, flax, sunflower, and oat that have a production value over $100 million. The relative ranking of crops produced in the world is somewhat similar to that in the United States, but worldwide, wheat and rice are more important than they are in the United States (Figure 2-6).

Livestock

Farmers feed crops such as corn, soybean, and hay to beef and dairy cattle, sheep, and goats. As compared to cattle, they feed poultry and hogs a greater proportion of high-energy concentrate feeds such as processed corn and soybeans. There are about 100 million beef and dairy cattle in the United States. The sale of milk from the nine million dairy cows is valued at more than $26 billion, and meat production from the 52 million dairy and beef cattle is valued at $49 billion. There are about 6.2 million sheep and lambs with a market value of $521 million. Total poultry production in 2005 was valued at more than $28.2 billion and included the sale of chicken broilers, chicken eggs, and turkey meat.

TABLE 2-8

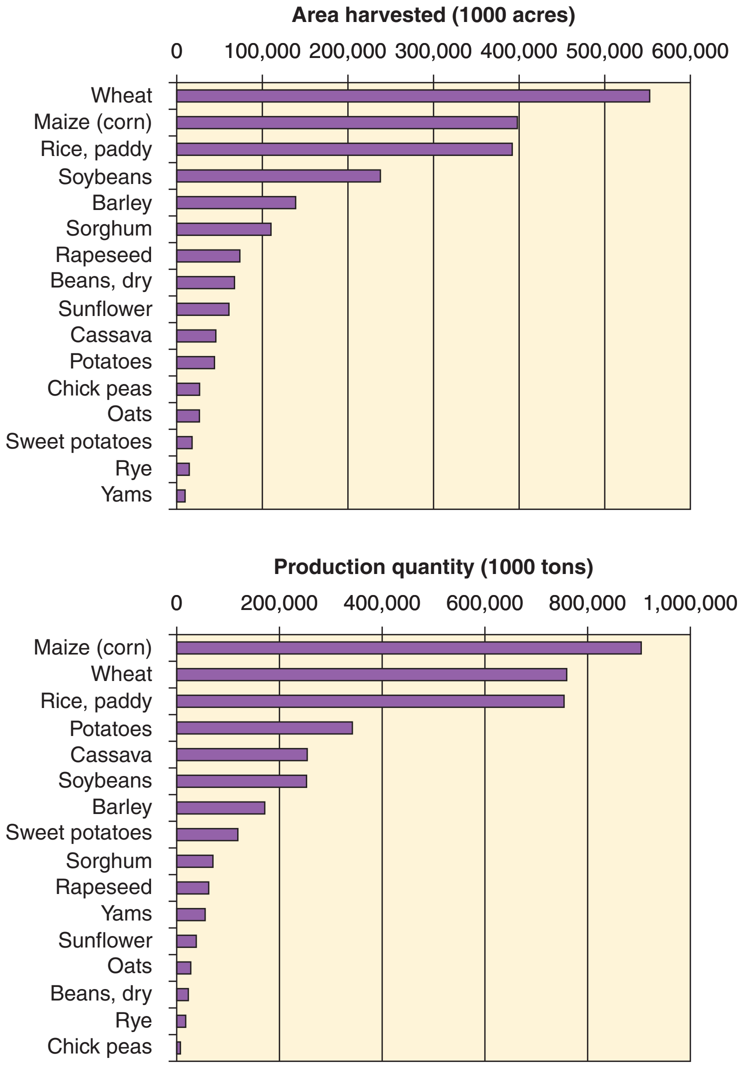
Area and value of crops in the United States, 2009. 1 acre = 0.4 hectare. *USDA-NASS (2010).*

Crop	Harvested acres	Total value ($)
Corn	79,590,000	48,588,665,000
Soybean	76,372,000	31,760,452,000
Hay	59,755,000	14,990,083,000
Wheat	49,868,000	10,626,176,000
Cotton	7,528,700	3,735,564,000
Sorghum	5,520,000	1,242,196,000
Barley	3,113,000	917,500,000
Rice	3,103,000	3,145,521,000
Sunflower	1,953,500	444,795,000
Edible bean	1,463,000	793,722,000
Oat	1,379,000	216,566,000
Sugar beet	1,148,600	1,289,621,000
Peanut	1,081,000	835,172,000
Potato	1,045,000	3,452,276,000
Canola	814,000	237,669,000
Tobacco	354,240	1,515,159,000
Flax	314,000	64,817,000
Rye	252,000	33,427,000

The Importance of Farming

Farming provides the food essential for our sustenance. Although international trade provides us with more diverse foods than in the past, a reliable and healthy food source is essential to our nation's security. Because of the high level of agricultural productivity, fewer people are directly employed in farming than ever before in our nation's history. Even though their numbers have decreased to 1 percent of the population, American farmers produce more food and fiber than ever before.

Today, each farmer produces food and fiber for about 150 people. The cost efficiency of U.S. farming has resulted in Americans paying only about 10 percent of their disposable income for food. This amount is less than anywhere else in the world and therefore, Americans have more money available to purchase other goods and services.



Food and Agriculture Organization of the United Nations (2010).

FIGURE 2-6
World production (acreage and production quantity) of selected crops in 2008. 1 acre = 0.4 hectare, 1 ton = 0.9 tonnes, and 1 pound = 0.45 kilogram.



A Family Dairy Farm

Today, many farms have become very large in order to spread the costs of equipment, land, and animals over greater production, thereby reducing the costs per unit of product produced. Larger farms also gain advantages with cost discounts from large purchases of production inputs such as fertilizers, chemicals, and feed ingredients, and in marketing larger quantities of products such as milk, meat, or grain. For the consumer, the end result is relatively low cost milk products. The large farm is often owned by a family that manages and provides labor. Hired labor is also employed.

Large dairies of 1000+ cows are becoming commonplace throughout the United States. These dairies specialize in milk production and contain no other type of livestock. The animals are confined in large, free-stall barns and milked three times a day in modern milking parlors. Farmers use computer programs and advisors to formulate the most cost-effective rations for cows at a particular stage of lactation. Average annual milk production of nearly 24,000 pounds (10,900 kilograms) per cow in the Midwestern dairy states of Minnesota and Wisconsin is not uncommon.

The large quantities of manure produced per cow (about 100 pounds, or 45 kilograms, per day) is stored as liquid in large lagoons and then transported to the fields. Large dairy farms often have more than 1000 acres (401 hectares) of land on which to grow feed ingredients. They typically grow corn for grain and silage, and alfalfa for hay and haylage (see Chapter 17). Farms need silos for silage and barns for hay and grain. These farms often also grow soybeans, but because raw soybeans contain chemicals that inhibit digestion, they must be processed before they are given to livestock as feed. Other feed ingredients such as supplementary vitamins and minerals are purchased off-farm. For crop production and harvesting, animal feeding, and manure handling, farmers use large tractors (200 horse power [hp]) and other machinery to increase speed of production and to decrease operating costs. Many farmers also use bovine somatotropin (BST), an injected hormone, to increase milk production efficiency.

A financial analysis for a large 500+ cow dairy enterprise in Minnesota by FINBIN, the Farm Financial Database (http://www.finbin.umn.edu) showed a net return of about $240 per cow with the following costs and returns per cow:

- Gross returns: $3095/cow based mostly on sales of about 24,000 pounds/cow at $13.66 per hundred weight
- Direct costs: $1970/cow including feed ($1200/cow); veterinary and breeding ($170/cow); repairs, fuels, trucking ($200/cow); BST hormone ($77/cow); hired labor ($73/cow); bedding ($78/cow); miscellaneous supplies and expenses ($172)
- Overhead expenses: $884/cow including labor ($453/cow); machinery, building, utilities ($230/cow); interest on loans ($130/cow); miscellaneous expenses

Economic Impact

Farming is the foundation of the huge food and fiber industry within the U.S. economy (Tables 2-9 and 2-10). In total, the food and fiber sector adds about 12 percent, or $150 trillion, to the **gross domestic product (GDP)** of the United States (a measure of the value of the nation's total production). Farming itself contributes about $140 billion, or 1 percent, to the GDP and 6 percent to the food and fiber section.

TABLE 2-9

Contribution of farming and other segments of the food and fiber system to the gross domestic product (GDP), and to jobs in 1972 and 2001. *Adapted from USDA-ERS (2004b).*

	% of GDP		% of jobs	
	1972	2001	1972	2001
Foodservice	8	13	15	28
Transportation	4	3	3	2
Trade	27	27	25	35
Services	20	27	18	14
Other manufacturing	13	8	8	5
Textiles	5	2	9	3
Food processing	12	14	8	5
Farm	11	6	14	8

TABLE 2-10

Contribution of important industries to the gross domestic product of the United States in 2009. *U.S. Department of Commerce–Bureau of Economic Analysis (2010).*

Total	Billions $	%
Agriculture, forestry, fishing, and hunting	136.4	1.0
Mining	231.3	1.6
Utilities	269.2	1.9
Construction	578.3	4.1
Manufacturing	1,568.60	11.0
Wholesale trade	793.3	5.6
Retail trade	842.2	5.9
Transportation/warehousing	393.9	2.8
Informatics/media	633.8	4.4
Finance, insurance, real estate	3,057.80	21.4
Professional and business service	1,723.90	12.1
Education, health care, social assistance	1,188.80	8.3
Arts recreation, food services	545.6	3.8
Government	1,932.50	13.6

Agricultural Exports and Imports

Agricultural exports, the farm products that are shipped to other countries, play a significant role in the overall U.S. economy (Table 2-11, Figure 2-7). **Agricultural imports** are the farm products that other countries ship to the United States (Table 2-12). Currently, agricultural exports total $115 billion and exceed

TABLE 2-11

Value of selected agricultural exports, 2008. *Adapted from USDA–Foreign Agricultural Service (2010).*

Export crops	$ Million
Soybean	15,469
Wheat	11,604
Corn	13,454
Fruits/nuts	8,622
Cotton	4,829
Vegetables	5,130
Tobacco	1,238
Livestock	
Beef and pork	8,783
Poultry	5,053
Total of all agricultural exports	**115,439**

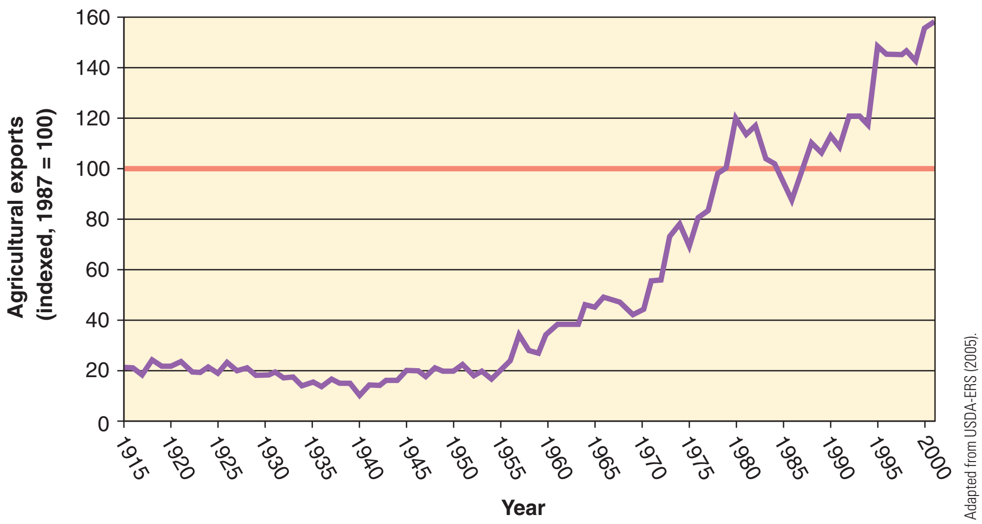


FIGURE 2-7
The trend in U.S. agricultural exports. Exports increased dramatically in the last half of the twentieth century.

TABLE 2-12

Value of selected agricultural imports, 2008. *Adapted from USDA–Foreign Agricultural Service (2010).*

Import crops	$ Million
Grains and feeds	8,260
Fruits	7,896
Vegetables	8,314
Sugars	2,967
Oilseeds	6,767
Coffee	4,412
Cocoa	3,299
Livestock	
Beef and pork	4,818
Dairy products	3,138
Total of all agricultural exports	**80,465**

agricultural imports, which total $80 billion. Corn and soybean are the leading agronomic crops that are exported. Grain-fed beef and pork are leading livestock exports. About 25 percent of all U.S. agricultural products are exported around the world. The top countries to which the United States exports agricultural products are Canada (fruit and vegetables), Mexico (corn and soybean), China (soybean and cotton), and Japan (corn and soybean). Canada and Mexico are also the top countries from where agricultural imports come to the United States. Farmers and farm organizations also depend on export demands to maintain the price of certain commodities such as corn and wheat.

Agricultural Jobs

The food and fiber industry provides jobs for 23 million Americans. Of these, about 2.3 million people, or 1 percent, are directly employed in farming. Other agriculturally related jobs are in various areas of agriculture such as chemical fertilizer and pesticide production, crop consultants, seed and equipment dealers, food processing, and food wholesaling, to name just a few.

Agribusiness

The food and fiber sector is often called **agribusiness** and includes all firms engaged in producing, processing, transporting, marketing, and distributing products.

1. *Farmers or ranchers* produce the raw materials that are ultimately transformed into fuel, food, and fibers. They purchase inputs and services and sell to food processors. Farmers provide the management, intellect, and labor to produce

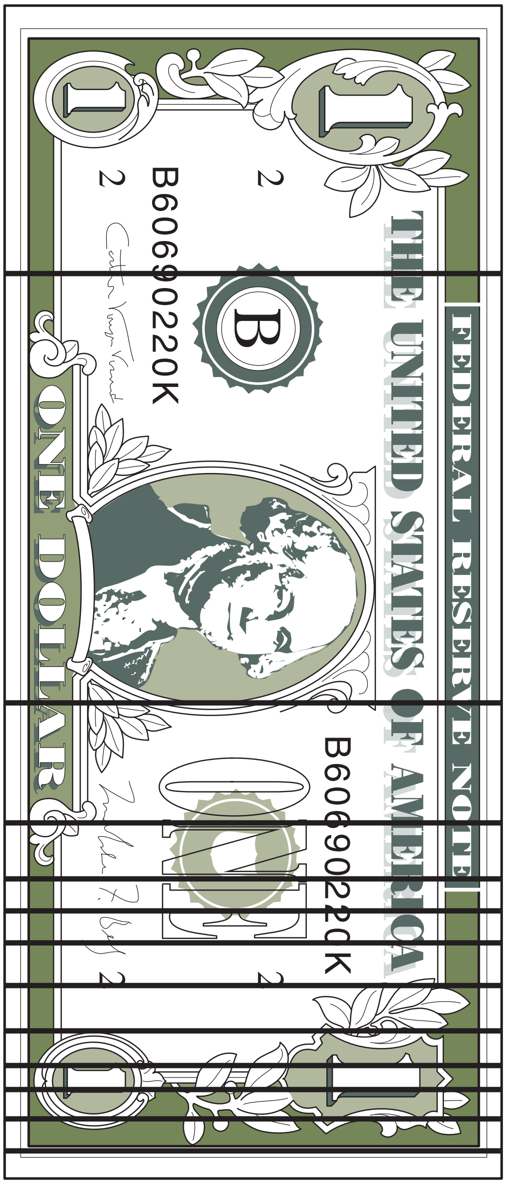


FIGURE 2-8
Where your food dollar goes. In 2006, only 19 percent of food costs went to farm value.

the raw material. They are also exposed to weather and market risks. The majority of the cost of food that consumers pay goes to other parts of agribusiness besides farming (Figure 2-8).

2. *Farm input/service suppliers* provide seed, fertilizers, pesticides, and equipment necessary to grow a crop. Some are small local businesses, whereas others are large multinational corporations. Small businesses are located in rural communities and include crop consultants, insurance agents, banks, hardware stores, and seed, fertilizer, and equipment dealerships. They may also be grain or livestock buyers at the local elevator or stockyards as well as haulers

and shippers. Examples of large businesses include companies such as John Deere and Ford-New Holland that provide tractors as well as tillage, planting, and harvest equipment. Seed and genetics companies such as Pioneer Hybrid International and Monsanto are also examples of large businesses.

3. *Food and fiber processors* convert raw materials or commodities such as grains and livestock produced on the farm into products that can be sold to consumers. Multiple businesses or a single business may be involved in processing. Commodity processors buy raw material such as grain or livestock and do the initial conversion to food or industrial ingredients. Food or industrial product-processors then take ingredients from multiple sources and create a marketable product. Examples include the following:
   - Wheat is obtained by a miller and ground into flour. The flour is then processed into food products such as bread and pasta. It can also be used to produce dough onto which cheese, tomato sauce, and spices are added to make pizza.
   - Corn is subject to milling and is separated into starch and other products. Corn starch is then converted into high fructose corn syrup. The high fructose corn syrup is then purchased by beverage companies to use as a sweetener.
   - Barley is converted into malt by a malting company. The malt is then purchased by a brewing company for production of beer.
4. *Marketers* link the food processor to the consumer. This involves wholesale and retail sales as well as on-time delivery. Today, in contrast to much of the twentieth century, food is distributed nationally and internationally. For example, rice that is grown in Arkansas is sold in New York on the supermarket shelf as part of a processed product. Our current food production and distribution system provides an exceptional array of low-cost foods to consumers.

Vertical Integration of Agribusiness

Much food and fiber production has some level of vertical integration. **Vertical integration** of agribusiness occurs when a single firm controls several stages in the production of food and/or fiber (Figure 2-9). Vertical integration enables coordinated production, increased efficiency among operations, and ultimately low prices for the consumer. ConAgra Foods, Cargill, and Tyson Foods have vertical investments in the food business. Following is a partial description of ConAgra Foods' vertical integration in the food industry either through direct ownership, subsidiaries, or alliances.

- Foods processed and marketed include: Peter Pan peanut butter, Chef Boyardee, Healthy Choice diet foods, Wesson Oil, Hunt's tomato sauce, Butterball turkeys, and Swift and Armour meat brand products.
- Commodity processing: ConAgra owns grain-milling facilities and poultry-, beef-, and pork-processing facilities.
- Commodity production: ConAgra produces cattle, poultry, and swine.
- Inputs and services to farmers: ConAgra owns elevators for grain collection and transportation systems, and it distributes chemicals, fertilizers, and seed.

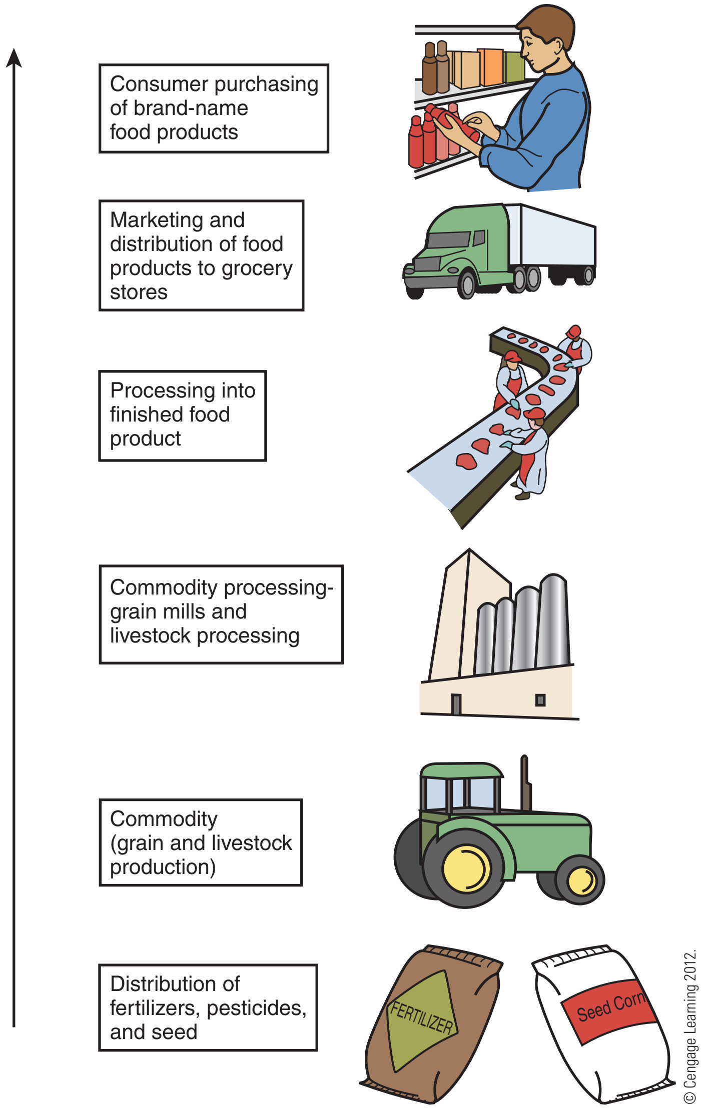


FIGURE 2-9 Vertical integration of agribusiness. In this example, a single corporation controls all aspects of food production from the farm to the consumer's table.

Agribusiness Concentration

The food and fiber agribusiness field has undergone considerable consolidation. This has resulted in the concentration of some aspects of the food production system. Concentration occurs when a small number of companies control a significant number of activities within the food and fiber production sector. An example is in the beef and pork livestock slaughter and processing industry where most of the operations are controlled by a few companies. On a retail level, marketing of some foods is also concentrated. For example, most breakfast cereals and candies are marketed by a few large producers. Vertical integration and concentration within the food industry has led to efficiency and reduced consumer prices, but some are concerned that because large business controls the food system, we are lacking a free market.

United States Farm Policy

Agriculture and farming have long been recognized as critical activities for the United States. Consequently, legislation has been enacted to support and stabilize agriculture. Some of the consistent goals in U.S. farm policy have been to

- stabilize price of important crops and livestock by providing crop insurance and payments to farmers and by preventing commodity surpluses,
- support an agricultural export industry to insure a world market for commodities,
- conserve and protect environmental resources for the general public and the future of farming.

Some of the important legislative actions include the development of agricultural institutions and farm bills.

Federal Institutions

In the late 1800s, more than half of the U.S. population was directly or indirectly involved in agriculture. The U.S. government recognized the need for improving agriculture through research and education, and it created the following institutions.

- **Land-grant universities—1862.** The Morrill Act established the land-grant university system to support agricultural education for the average person. The act provided land or federal monies for the creation of state colleges to teach agriculture and mechanic arts. Iowa became the first state to authorize a land-grant college (Iowa State University).
- **The United States Department of Agriculture—1862.** The USDA was charged with conducting scientific experimentation on new seeds and plants and then to distribute the information. The mission of the USDA has evolved to meet the needs of modern agriculture and is discussed in the next section of this chapter.
- **Agricultural experiment stations—1887.** The Hatch Act provided funds to support agricultural research in every state. Agricultural experiment stations were linked to land-grant colleges. Agricultural experiment stations conducted the first applied research on improved production practices such as fertilizers and crop varieties. Agricultural experiment stations still conduct basic and applied research to address the needs of farmers and consumers.
- **Extension education for farmers—1914.** The Smith–Lever Act authorized the creation of an extension education system at the land-grant colleges. The extension education system was established to educate and transfer research information to farmers.
- **Soil conservation service—1935.** The USDA soil conservation service (now called the Natural Resources Conservation Service) was established to promote soil conservation practices such as contour strip cropping as well as tree and native grass planting. Creation of this agency was in large part a response to the severe soil erosion that occurred in the Dust Bowl (see Chapter 11).

The Minnesota Agricultural Experiment Station

The Minnesota Agricultural Experiment Station was established in 1885 at the University of Minnesota with the purpose of promoting agriculture through scientific investigations. Beginning in 1887, research activities were federally funded by the Hatch Act, which helped many land-grant universities implement research programs. Much of the original research was related to solving applied agricultural problems. The Minnesota Experiment Station was renowned for its early work in plant improvement through breeding. Plant breeders, such as Willet M. Hayes, used their scientific knowledge of plant genetics and breeding to develop the first varieties of wheat, barley, flax, oat, alfalfa, and corn adapted to the Midwestern environment.

Wheat was a priority for early breeding experiments (Figure 2-10). In the late 1800s and the early 1900s, wheat was the most important crop in the Midwest, with nearly 6 million acres grown in Minnesota alone. In Minneapolis, the world center of wheat milling for flour production, the Mississippi River powered more than 400 flour mills. However, farmers were using non-selected "landrace" seed that had yields of only about 10 bushels per acre. In 1899, Hayes released "Preston," an improved wheat variety.

Successful collaboration among scientists has been a long tradition of the experiment station system. Cereal chemists at Minnesota were the first to study the chemistry of the wheat starch and conduct analytical tests on the milling and baking quality of wheat. Plant pathologists first studied wheat stem rusts that severely reduced wheat yields and collaborated with plant breeders in developing the first rust resistant wheat varieties such as "Marquillo" (1928) and "Thatcher" (1934). Additional breeding and use of new genomic techniques over the past 100 years have resulted in the release of more than 35 improved varieties that have greatly increased the profitability of wheat production and provided inexpensive wheat products to consumers.

Today, the role of the Minnesota Agricultural Experiment Station has expanded to meet the needs of a diverse clientele. Funding now supports



University of Minnesota, Agricultural Experiment Station.

FIGURE 2-10
Early wheat breeding research on St. Paul campus of the University of Minnesota.

(*Continued*)

basic and applied research in agriculture, forestry, horticulture, human nutrition, environmental quality, and family and community life. More than 400 research projects and 300 faculty members are supported in research throughout the state. The University of Minnesota Extension Service uses the research results in educational programs that they conduct. The impact of this agricultural research has immediate benefits in the Midwest that influence the national economy. Many of the discoveries relating to soil, climate, and crops also benefit the rest of the world.

The United States Department of Agriculture (USDA)

The USDA is the federal agency with responsibility for national leadership on food, agriculture, and natural resources. The agency has about 100,000 full- and part-time employees. The head of the USDA is the secretary of agriculture, who is appointed to the position by the president of the United States and confirmed by the U.S. Senate. The USDA was established in 1862 by Abraham Lincoln. The secretary of agriculture sits on the Cabinet of the president of the United States. The USDA has established seven mission areas with federal agencies to administer the program areas (Table 2-13).

USDA Mission Areas

Farm and Foreign Agricultural Services Agencies provides financial stability for farmers who continually face the risk of low market prices and weather that can damage yield. This support is essential to having a sustainable food supply in the United States. The Farm Service Agency (FSA) administers commodity credit as well as conservation, disaster, and emergency assistance programs. The Risk Management Agency (RMA) provides crop insurance for producers.

Food, Nutrition and Consumer Services deals with hunger and food-related health issues in the United States. The Food and Nutrition Service Agency administers domestic nutrition assistance programs. An example is the food stamp program. The Center for Nutrition Policy and Promotion provides science-based dietary guidance and nutrition education. This area takes up the largest portion of the USDA budget.

The Food Safety and Inspection Service inspects meat, poultry, and egg products to insure that they are safe to eat and are labeled properly. The protection of our food supply is critical for the well-being of our citizens. Recent outbreaks of illness brought on by contamination of food with *E. coli* and *Salmonella* have heightened our awareness of the necessity of food inspection.

Marketing and Regulatory Programs has three agencies. The Agricultural Marketing Service promotes domestic and international marketing of agricultural products. The Animal and Plant Health Inspection Service (APHIS) controls the movement of plants, animals, and agricultural products into the United States. They also establish quarantines to protect our agriculture and natural resources from nonnative pests. The Grain Inspection, Packers, and Stockyards Administration (GIPSA) and the Federal Grain Inspection Service (FGIS) provide farmers, handlers, processors,

TABLE 2-13

Listing of agencies within the USDA. *USDA (2010).*

Agency	Acronym/ abbreviation	Function
Agricultural Marketing Service	AMS	Facilitates marketing of agricultural products nationally and internationally; ensures fair trade
Agricultural Research Service	ARS	Conducts agricultural field and laboratory research
Animal and Plant Health Inspection Service	APHIS	Ensures health and care of animals and plants
Center for Nutrition Policy and Promotion	CNPP	Works to improve the health of Americans by developing and promoting nutrition guidelines
Economic Research Service	ERS	Conducts agricultural economic research
Farm Service Agency	FSA	Implements policy; administers credit and loan programs; manages marketing programs
Food and Nutrition Service	FNS	Provides children and low-income people with food to increase food security
Food Safety and Inspection Service	FSIS	Ensures nation's food supply is safe
Foreign Agricultural Service	FAS	Builds new foreign markets for U.S. agriculture
Forest Service	FS	Sustains health of U.S. forests and grasslands
Grain Inspection, Packers, and Stockyards Administration	GIPSA	Facilitates marketing of agricultural products; monitors industry trade practices
National Agricultural Library	NAL	Ensures access to agricultural information
National Agricultural Statistics Service	NASS	Provides agricultural and rural data to monitor U.S. agriculture and carry out farm policy
National Institute of Food and Agriculture	NIFA	Advances research, extension and higher education in food and agricultural sciences.
Natural Resources Conservation Service	NRCS	Helps people conserve, maintain, and improve natural resources and the environment
Risk Management Agency	RMA	Provides financial tools to manage agricultural risks
Rural Development	RD	Helps rural areas to develop and grow

exporters, and international buyers with sampling, inspection, process verification, and weighing that describes the quality and quantity of grains in commerce. The Packers and Stockyards Program (P&SP) promotes fair business practices and competitive environments to market livestock, meat, and poultry.

Natural Resources and Environment Agencies works to prevent damage to natural resources and the environment, restore the resource base, and promote good land management. The Natural Resources Conservation Service (NRCS) is the

primary federal agency that works with private landowners to conserve, maintain, and improve their croplands and grazing lands. For example, NRCS works with another agency, the FSA, to facilitate the CRP to provide for the protection of vulnerable landscapes throughout the United States. The Forest Service (FS) administers programs for applying sound conservation and utilization practices to national forests and national grasslands, for promoting these practices on all forest lands through cooperation with states and private landowners, and for carrying out extensive forest and range research.

Research, Education, and Economics integrates research, analysis, and education to provide a sustainable and competitive food and fiber system, as well as strong rural communities and families. There are several agencies that contribute to this mission. These include the Agricultural Research Service (ARS) that conducts agricultural research, the Economic Research Service (ERS), and the National Agricultural Statistics Service (NASS) that collects and interprets agricultural production, environmental, and economic data. Much of the agricultural statistical information used in this text was collected by ERS and NASS. The National Institute of Food and Agriculture (NIFA) works in partnership with land-grant universities and other organizations to advance research, extension, and higher education in the food and agricultural sciences.

Rural Development improves the economy and quality of life in rural America by providing financial support for essential public facilities and services such as water and sewer systems, housing, health clinics, and electric and telephone service.

USDA Budget

Total USDA expenditures are estimated at about $146 billion in 2011. Roughly 84 percent of expenditures, or $123 billion in 2011, will be for mandatory programs that provide services required by law. This includes many of the nutrition assistance, commodity, export promotion, and conservation programs. $146 billion is a lot of money, but compared to the total federal budget of $2.6 trillion, it is a relatively small amount to support an organization that has responsibility for protecting our food sources and natural resources. We have provided the budget (Table 2-14).

Farm Bills

Funds to support agricultural programs and the USDA are provided in U.S. **farm bills**. The first of these was enacted in 1933. The Agricultural Adjustment Act, created during the great world economic depression that began in 1929, was critical to prevent widespread farm failures. Initially farmers received financial benefits in return for limiting production and participation in soil conservation programs. Subsequent farm bills (introduced at about 5-year intervals) have used various strategies to achieve the goals of income support for farmers, low food prices, and soil conservation. Beginning in the 1970s, food stamps and other food distribution programs to combat poverty and hunger were included in farm bills. During the development of each farm bill, all citizens can have input. Farmers' groups, agribusiness, and environmentalists have significant lobbying efforts, and a compromise bill is developed. Following authorization, Congress must then fund or appropriate monies for the various provisions of the bill. The 2008 Farm Bill will govern federal agricultural programs until 2013.

The USDA-Agricultural Research Service (USDA-ARS)

The ARS is the primary scientific research agency of the USDA. It has a $1 billion budget supporting more than 2000 scientists stationed at more than 100 locations throughout the country. ARS scientists have a long history of significant research accomplishment in response to national needs. An example is the ongoing research on alfalfa improvement that is being conducted at the ARS Plant Science Unit at the University of Minnesota in St. Paul. Alfalfa is among the most valuable field crops grown in the United States and is widely used as a livestock feed for dairy and beef animals and to supply nitrogen to other crops growing in rotation. The Plant Science Unit has had a remarkable history of improving alfalfa to increase the profitability of agriculture in the United States. Scientists in that unit were the first to develop winter-hardy alfalfa germplasm with unique disease resistance to organisms such as *Phytophthora* root rot that destroys the root system of alfalfa and reduces its persistence. They later conducted the first research on the dynamics of biological dinitrogen fixation (see Chapter 8) in alfalfa and released the alfalfa variety "Nitro" to supply nitrogen in short-term crop rotations. The results of this research are still relevant today as farmers around our nation struggle with finding alternative sources of nitrogen fertilizer in organic and conventional crop-production systems.

In response to the current national need for production of ethanol from cellulosic biofuels, scientists in the Plant Science Unit are developing a new biofuel-type alfalfa that is taller and that has more ethanol production potential than current varieties (Figure 2-11). They are collaborating with colleagues at another ARS facility, the Dairy Forage Research Laboratory in Madison, Wisconsin, in discovering ways to increase the ethanol production of the plant by changing the cell wall structure of the plant stem. To add additional value to the alfalfa crop, these ARS scientists are working to produce new biodegradable plastics and adhesives from alfalfa.



Bruce Fritz, USDA-ARS.

FIGURE 2-11
USDA-ARS scientists compare the biomass of an alfalfa plant selected for use in biofuel production (plant on left) with a smaller alfalfa plant bred for livestock forage (plant on right).

TABLE 2-14

USDA budget for 2011. *USDA (2010)*.

Category	% of $146 billion budget
Food assistance and nutrition	70
Farm and commodity programs	17
Conservation and forestry	7
All other	6

The 2008 Farm Bill, also titled the Food, Conservation, and Energy Act of 2008, provides authorization for congressional funding in 15 areas called "titles" that include many of the missions of the USDA. The titles and some of their provisions in the 2008 Farm Bill include the following:

Title I. Commodities. This title allows for various forms of payments to eligible producers who produce wheat, corn, barley, grain sorghum, oats, upland cotton, soybeans, dry beans, peas, lentils, and chickpeas. Payments are also provided to dairy producers to support the price of milk. For some who feel these programs subsidize industrial agriculture, this title is the most controversial part of the Farm Bill; however, many farmers and farm groups feel that the payments ensure a reasonable return to producers and reduce production risks, allowing them to continue to farm.

Title II. Conservation. This title encourages soil and water conservation on actively farmed lands and also promotes wetland restoration. The program includes funding for the Conservation Reserve Program (CRP). The Environmental Quality Incentives Program (EQIP), administered through the NRCS, provides technical assistance and payments to help crop and livestock producers with environmental and conservation improvements (e.g., terracing, fencing for rotational grazing, manure holding areas) on land used for agricultural production. In 2008, the bill contained a special provision providing assistance to producers for farming and land-management activities that improve water and soil in the Chesapeake Bay Watershed.

Title III. Trade. This title provides for the promotion of trade of U.S. commodities to other countries. Some specific components include the Food for Peace Act that provides for sales of agricultural commodities to developing countries on credit or grant terms, for donation of U.S. agricultural commodities to meet emergency and nonemergency food needs in foreign countries, and for donation of U.S. agricultural commodities to governments of least developed countries. The McGovern–Dole International Food for Education and Child Nutrition Program donates commodities and financial and technical assistance for preschool and school feeding programs in developing countries.

Title IV. Nutrition. This title provides ongoing funding for the Food Stamp Program or Supplemental Nutrition Assistance Program. Use of this program by U.S. citizens is at an all-time high during these times of high unemployment in the ongoing U.S. economic recession. In February 2010, about 40 million people, or one in eight Americans, were enrolled for food stamps. The Farm Bill also provides for the National School Lunch Act (NSLA) and provides for

over $50 million annually for purchase of fresh fruits and vegetables for use in participating schools and service institutions.

Title V. Credit. This title provides for some unique loans for qualified individuals who wish to purchase family-sized farms. It also provides for operating and emergency loans for producers.

Title VI. Rural Development. This title includes various aspects of rural community and economic development programs. The current program emphasizes value-added agricultural activities, including renewable energy and regionally produced agricultural products.

Title VII. Research. This title provides funding of $700 million annually to support competitive grants under the Agriculture and Food Research Initiative (AFRI) for fundamental and applied research and education. Much of this research is conducted at cooperating land-grant universities throughout the United States. Areas of focus for this research are:

- plant health, plant production, and plant products
- animal health, animal production, and animal products
- food safety, nutrition, and health
- renewable energy, natural resources, and environment
- agriculture systems and technology
- agriculture economics and rural communities

Title VIII. Forestry. This title provides for new forest preservation programs and tightens restrictions on importation of illegally harvested wood products. It also provides federal matching grants to help local governmental entities, Native American tribes, or nonprofit organizations acquire private forest land threatened by conversion to nonforest uses.

Title IX. Energy. Within this title, a program was established to partially pay for the establishment, production, harvest, storage, and transportation of bioenergy crops to conversion facilities. This program shows the national priority given to bioenergy development and was aimed at incentivizing growth and processing of crops for this new industry. Within this same title, a granting program was authorized to assist development and construction of demonstration-scale biorefineries to convert biomass to biofuel and other high-value products.

Title X. Hort and Organic Agriculture. Within this title, a program was established that authorizes grants to enhance production and marketing of specialty crops such as fruits, nut crops, and flowers. Funding is also provided for farmers' markets and to expand fruit and vegetable market news reporting. Funding is also provided to help organic producers and handlers pay for certification costs (see Chapter 18), and to enhance data collection on organic agriculture.

Title XI. Livestock. An ongoing portion of this title is the Livestock Mandatory Reporting Act of 1999 that mandates the reporting of information ensuring a viable livestock industry. This information includes marketing, pricing, and supply-and-demand conditions of cattle, hogs (swine), and lamb. Another very different aspect of this title requires non-restaurant retailers to inform consumers of country of origin of commodities such as beef, lamb, and pork; chicken, farm-raised fish and shellfish; fresh fruits and vegetables.

Title XII. Crop Insurance. This title ensures the availability of crop insurance under several plans of insurance and coverage levels for a variety of crops.

Crop insurance policies are sold and serviced by private insurance companies under premium rates and contract terms set by the Federal Crop Insurance Corporation (FCIC) and administered by USDA's Risk Management Agency (RMA). Premiums and delivery costs are federally subsidized. The title provides disaster assistance payments to producers of eligible commodities (crops, farm-raised fish, honey, and livestock) in counties declared by the secretary of agriculture to be "disaster counties," and any farms with losses in normal production of more than 50 percent in a calendar year. It also provides payments to eligible producers for livestock death losses in excess of normal mortality due to adverse weather.

Title XIII.Commodity Futures. This title establishes and provides authority to the Commodity Futures Trading Commission (CFTC) over futures contacts and foreign currency options. Civil penalties can be applied for manipulation of market prices of any commodity.

Title XIV and Title XV. Miscellaneous and Trade and Taxes. These final two titles contain diverse, significant provisions such as agriculture biosecurity administration and education programs for socially disadvantaged farmers, the Agricultural Disaster Relief Trust Fund, and a tariff on ethanol imported for fuel use. It provides a temporary cellulosic biofuels production tax credit of up to $1.01/gallon through December 31, 2012.

Review Questions

1. What are some of the definitions of a farm? What constitutes a large farm or a hobby farm?
2. What is the average size of a farm in the United States?
3. What differentiates a small farm from a large farm? Which of these have the greatest overall production?
4. What is the difference between the original and current definitions of "acre"?
5. How much is the average income of a farm household, and where does this income come from?
6. What are the reasons for the USDA's financial support to growers?
7. What is the difference between commodity payments and conservation payments?
8. What portion of the entire U.S. land resource is used for agriculture? How much of this land is used for rotated crops?
9. Identify regions that have the most and the least use of land for grassland, cropland, forestland, and urbanization.
10. Which crops are grown most widely in the United States and have the greatest economic value?
11. What are the four steps in the movement of food from the farmer to the consumer?
12. What is an agribusiness? Give an example.
13. What is vertical integration of agribusiness? Give an example.
14. Discuss the contribution of farming to the U.S. gross domestic product and the economy.

15. What is the USDA, and what is its mission?
16. Discuss the history of the agricultural experiment station.
17. What is the Farm Bill? Identify and discuss a title within the Farm Bill.

Critical Thinking

1. This chapter discussed much of the economics involved with farming. Subsidies supplement the farmer's income so that food prices can be kept low and so that farmers can stay in business. Research and write a short essay on the farm subsidies of your state. Where does your state rank in total subsidies? Who are the largest recipients? Do you think that farm subsidies are necessary?
2. Review the diversity of employment opportunities associated with producing, processing, and marketing of a food that you eat. Have you ever been employed in the food production, processing, marketing, or sales industry?
3. Go to the USDA-ARS website by using a simple search engine. At the website, locate a USDA-ARS site near you and review the research programs. For a specific research program, review the objectives, methods, and accomplishments.
4. Should the United States allow vertically integrated agribusinesses to participate in the food system? What are the advantages and disadvantages?
5. Conduct an in-depth review and analysis of one of the titles within the Farm Bill in order to understand the complexity of the legislation.

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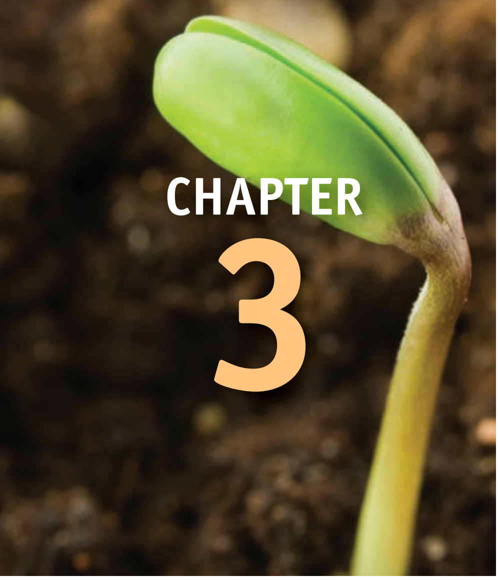
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CHAPTER 3



Feeding the World



Key Concepts

- Human population continues to grow worldwide because of advancement in medical science and agriculture.
- The food supply continues to grow because of advances in agricultural technology.
- Soil, water, and energy resources are critical for agriculture, and conserving these resources is important to meet the food needs of future populations.
- World food supplies were greatly increased by the application of Green Revolution technology.
- A strategy to meet future world food needs includes preserving genetic resources, improving existing crops, developing new crops, and considering alternative approaches to crop production.

Key Terms

Alliance for a Green Revolution in Africa (AGRA)
arable land
Consultative Group on International Agricultural Research (CGIAR)
developed country
developing country
ecological footprint
Green Revolution
international research institutes
IPAT equation
world population



Introduction

In this text, we concentrate on crops and food production in the United States. However, in today's global economy, we are aware that our country has extensive economic and agricultural connections to the rest of the world. Soil, energy, and water resources are abundant in the United States and other developed countries, but they are lacking in many other parts of the world. The earth's resources may not be adequate to meet the needs of the ever growing population. Will agriculture be able to meet food needs in the future?

Human Populations

In the 1800s, the total **world population** was only about one billion, but since that time, the world population has exploded (Figure 3-1). By 2000, it reached six billion, and current trends indicate it will reach nearly nine billion by 2050. Population and population growth is unevenly distributed in the world. The developed world (e.g., United States, Canada, Western Europe, Japan, and Australia), with a population of about one billion, is growing at a rate of 0.1 percent per year. In contrast, the population of developing countries (in Africa, Latin America, and most of Asia) is more than five billion and is increasing at a rate of nearly 1.5 percent per year.

The exponential patterns of world population growth since the 1800s are due to better nutrition resulting from increased food availability, combined with the reduction of mortality due to improved sanitation, water purification, and medicine. The developments in medical science have been a major factor in prolonging life expectancy. The understanding of how disease spreads in water, and the development of vaccines for prevention and treatment of diseases such as smallpox, polio, tuberculosis, and influenza have greatly increased life expectancy.

Thomas Malthus, a British economist who observed the impact of the Industrial Revolution in England in the early 1800s, was one of the first to express concern that uncontrolled human population growth was unsustainable. He felt

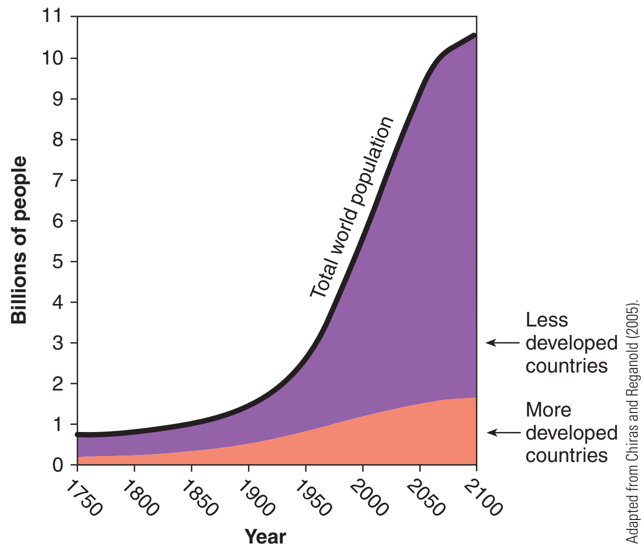


FIGURE 3-1
World population growth to the present, as well as projected growth.

that population growth would lead to disease epidemics and large-scale starvation until populations were in equilibrium with natural resources. Later, Paul Ehrlich, in his 1968 book *The Population Bomb*, warned that unhindered human population growth would decimate the earth's natural resources and result in widespread famine and wars by the end of the twentieth century.

Though localized famine has occurred in some regions of the world, the global catastrophic events predicted by Malthus and Ehrlich have not occurred. This is due in part to continued advancements in agriculture that have increased food supplies. Still, more recently, Norman Borlaug (1904–2009), a leader of developing improved wheat varieties to feed the world, declared in his 1970 Nobel Peace Prize speech, "If the world population continues to increase at the same rate, we will destroy the species."

Developing and Developed Countries

The world's nations can be classified into two broad categories: **developed countries** and **developing countries**. Developed countries have modern economies with a high per capita income and a high Human Development Index. The Human Development Index classifies countries by their level of well-being on the basis of education, standard of living, and life expectancy. The term *developing* may be something of a misnomer because countries on this list may not necessarily be improving their economic situation or quality of life.

Developed countries include the United States, Canada, Japan, Australia, countries in western Europe, Taiwan, and Israel (Figure 3-2). These countries have a high per capita national income that averages $30,000 per year and a high Human Development Index. Developing countries include countries in Africa, India, Central and South America, and Asia. These countries have a low per capita national income that averages $450 and a lower Human Development Index.

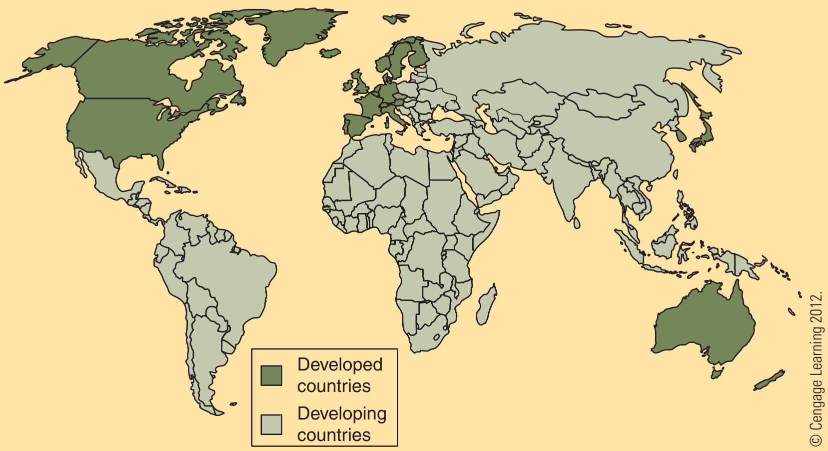


FIGURE 3-2 Countries of the world categorized by their state of development.

Global Food Production

The application of scientific technology to agriculture as described in this text has enhanced productivity of all crops and world food production. Plant breeding, fertilizers, irrigation, and improved crop management have all increased crop production per acre, although the production of crops has been greater in developed than in developing countries (Figure 3-3). Because of increased supply, food prices have decreased, although the impact of food prices on nutrition depends on one's relative income level (Figure 3-4). The rate of world food production and food production per capita has exceeded the population growth rate. Therefore, in theory, there should be adequate levels of food available to meet the needs of the world's population. However, the food available for consumption is not evenly distributed, and 1.02 billion people in 2009—17 percent of the world's population—face food insecurity, that is, a limitation in food that results in an inability to sustain an active and healthy life. Hunger is concentrated in underdeveloped countries (Figure 3-5). The rate of food insecurity in the world is increasing and was increasing even before the economic crisis began. Though total production of cereals such as wheat, barley, rice, and corn has increased, explosive population growth in some regions such as Africa has resulted in a decrease or only small changes in cereal production per capita (Figure 3-6). Cereal production in 2008 was at record highs, while at the same time a record number of the world's population was hungry.

Economic and Social Factors

Though the world has an abundance of food, not everyone has the opportunity to purchase it. More than a billion people in the world live in poverty, which is concentrated in developing countries. Poverty greatly limits the quantity and quality of food that people can purchase. Humans living in developed countries

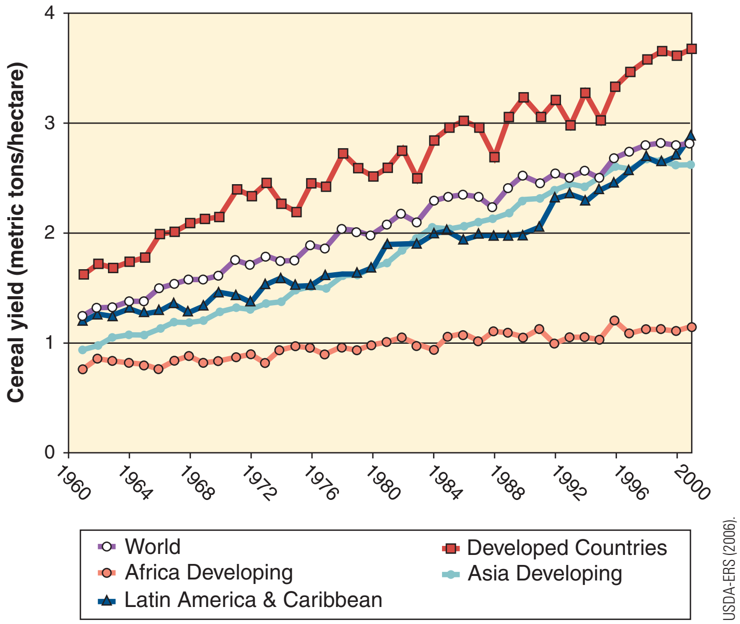


FIGURE 3-3
Cereal yields by region. 1 metric ton/hectare = 0.45 ton/acre.

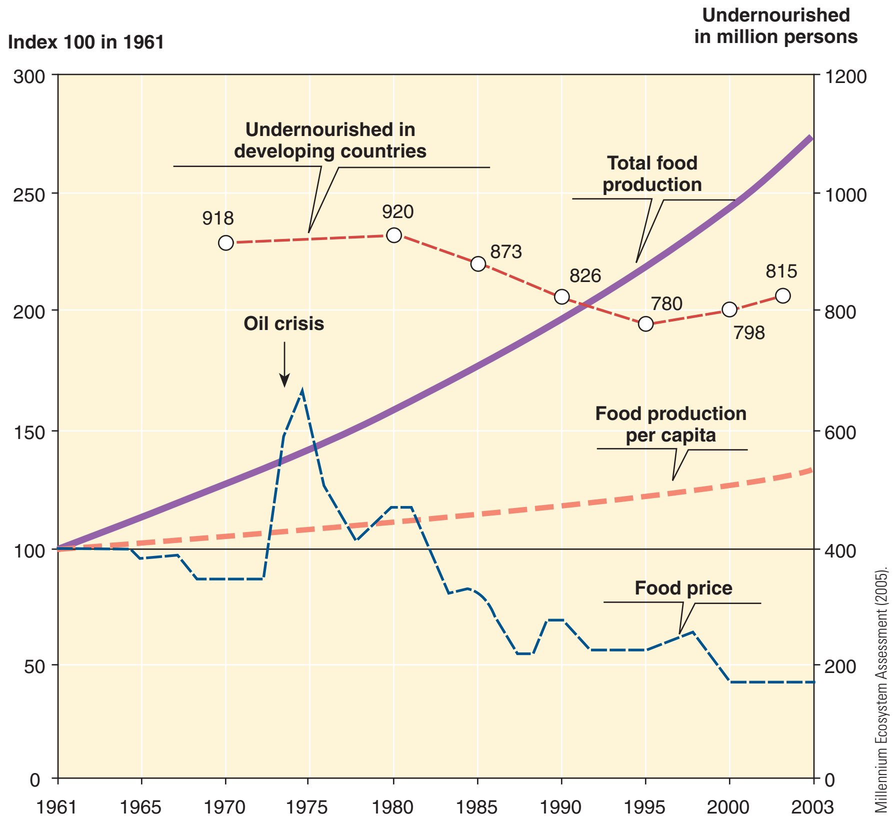


FIGURE 3-4
Total world food production has increased greatly, but the number of undernourished people in developing countries is still high. Food prices overall have been decreasing.

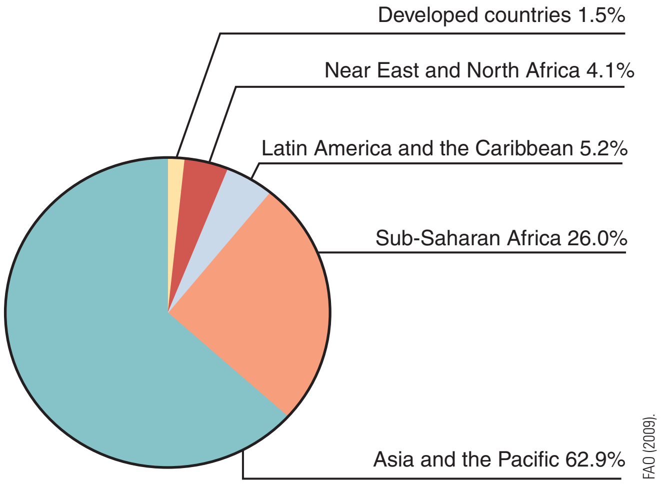


FIGURE 3-5
Percentage of food insecurity by region in 2009.

have greater economic wealth than those living in developing countries. Workers in developing countries often make only $1–2 per day (Table 3-1). With relatively less money in those regions, the economic demand for food is less, which in turn results in lower levels of either food production or distribution. The world economic crisis has caused reductions in employment and income in developing countries and has exacerbated world hunger.

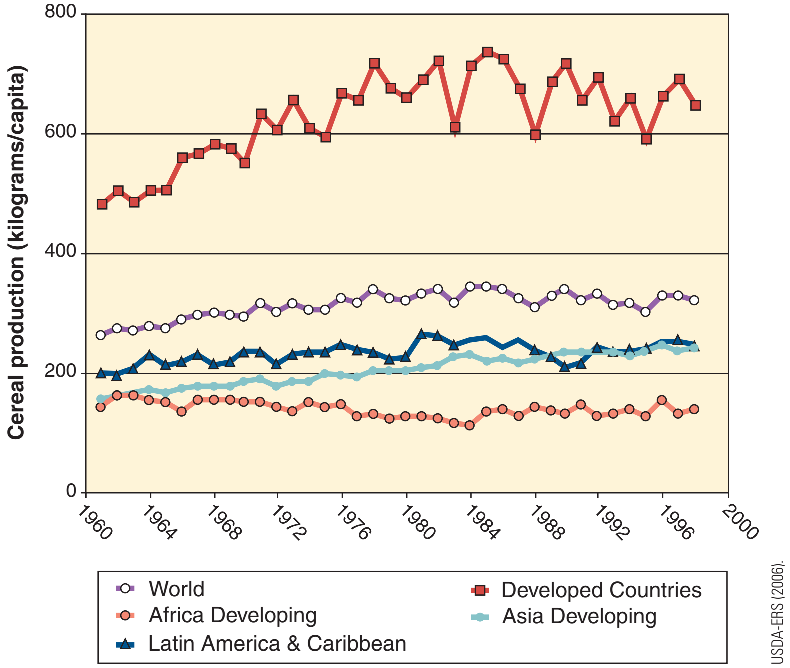


FIGURE 3-6
Cereal production per capita by region. 1 kilogram = 2.2 pounds.

TABLE 3-1

The percentage of population living on less than $1 per day. *Chen and Ravallion (2006).*

Region	Percentage of population
Developing regions	19.4
Northern Africa and western Asia	2.4
Sub-Saharan Africa	44.0
Latin America and the Caribbean	8.9
Eastern Asia	14.1
Southern Asia	31.2
Southeastern Asia and Oceania	7.3
Commonwealth of Independent States (former Soviet Republics)	2.5
Transition countries of southeastern Europe	1.8

World hunger issues are also greatly affected by other social and political issues. Many people in developing countries have been displaced from their homes and farms by war and other political events. Displaced persons living in refugee camps have little opportunity to grow food and may depend on aid from foreign donors. Governments often use food production and distribution to control people, and they may even disrupt agriculture for political gain. Destruction of crops and seed supplies is a strategy that is frequently used to cut off the food supply, and force subjugation and resettlement.

Environmental Limitations

As we discuss in other chapters in this book, many facets of the environment are important in the growth of crops. These include sunlight, climate, soils, and water. Within the distinct climatic conditions of the world, soils and water are among the most important factors limiting food production.

Soil Resources

Agricultural production systems throughout the world depend on soil resources and arable land. **Arable land** is land that is used or potentially could be used as cropland. Although arable land continues to be converted from other uses to agriculture, this rate of increase is less than 1 percent. In 2002, about 4.2 billion acres (1.7 billion hectares) were dedicated to crop production (Table 3-2). Most of the soils best suited for crop production are already in use, and now other less desirable land that requires high-input cost with lower yield potential is being converted. Some marginal lands may be prone to erosion and other degradation. In some cases, important ecosystems such as the tropical rain forests of South America are being converted to agriculture. This type of land acquisition may ultimately be unprofitable and have significant impacts on the global environment.

Future agricultural productivity may be limited by lack of resources. Farming practices are degrading agricultural soils, as are other human activities such as urbanization. It is estimated that worldwide about 12 million acres (5 million hectares) of cropland are lost annually. In many countries, better land-use planning would provide for long-term preservation of agricultural lands and reduce losses to urban sprawl. With urban populations expanding at four times the rate of rural populations, nearly three-fourths of the world's population may be living in urban environments within the next 50 years.

The extensive and sometimes exploitive use of our soil for agricultural production has led to some changes in their potential productivity. Based on estimates from the 1990s, about 40 percent of the world's cropland has undergone some

TABLE 3-2

Resources used or available per capita per year for basic needs in the United States compared to the rest of the world. *Pimentel et al. (1998)*.

Resources	United States		World	
Cropland	1.75 acres	0.71 hectare	0.67 acre	0.27 hectare
Pasture land	2.25 acres	0.91 hectare	1.41 acres	0.57 hectare
Forest land	2.47 acres	1.00 hectare	1.85 acres	0.75 hectare
Total land	6.47 acres	2.62 hectares	3.93 acres	1.59 hectares
Water (in 10^6)	0.45 gallon	1.70 liters	0.17 gallon	0.64 liter
Oil equivalents	2309 gallons	8740 liters	415 gallons	1570 liters
Forest products	2405 pounds	1091 liters	154 pounds	70 liters

amount of degradation. Erosion by wind and water is the main cause of degradation (affecting 4 billion acres [1.6 billion hectares], mostly in Asia and Africa), followed by loss of soil nutrients (336 million acres [136 million hectares], mostly in South America and Africa), and salinization due to poor water management on irrigated land (190 million acres [77 million hectares]). Agricultural practices such as overgrazing and deforestation of grazed land threaten the long-term productivity of more than 3.2 billion acres (1.3 billion hectares). These lands have a greater probability for desertification, as was observed during the Dust Bowl era. Global climate change will likely also cause a widespread shift in use of land for agriculture. Though some northern latitudes may have greater agricultural land use, the net worldwide effect is projected to be a loss of agricultural lands.

Water

Water is critical for all life and agriculture on the earth. It is the limiting factor on the use of many lands for crop and food production. Irrigation supplies water to some areas, and it has enabled reliable crop production in semiarid and arid regions. It has also enabled production on sandy soils in more humid regions. Irrigation of land for the production of crops was first practiced in the ancient Egyptian and Mesopotamian cultures (see Chapter 1). Today, more than 615 million acres (250 million hectares) are irrigated worldwide. Agriculture is the largest user of water (70%) compared to industry (20%) and human use for drinking and sanitation (10%). In the United States, agricultural irrigation and processing account for nearly 80 percent of the freshwater consumption. This is equivalent to nearly 500 gallons (1900 liters) per person per day. As populations continue to increase, agricultural water use will someday compete for direct consumption water use.

More than a billion people still lack access to clean drinking water and still billions more lack water for adequate sanitation. Already, in some portions of the world unsustainable water use is a concern. An example in the United States is in the Ogallala aquifer, one of the world's largest underground bodies of fresh water. This aquifer underlies portions of the Great Plains from southern South Dakota to Texas and is used to supply irrigation to produce corn, wheat, and cotton. These lands include the Dust Bowl region of the Southern Plains. This is the largest irrigation region in the United States, but its long-term productivity is threatened. Currently, the rate of water use greatly exceeds the rate of recharge, and the aquifer has receded, necessitating deeper and deeper wells. Other water supplies for use in crop production in other regions of the United States and in the world are likewise threatened.

Energy

Like many aspects of modern culture, industrialized agriculture requires energy (Table 3-3). Energy is used directly for fuel for transportation, machinery operation, and utilities for crop processing, heating, and lighting. Energy is also used indirectly in the production of synthetic fertilizer and pesticides. Total energy consumption (1.7 quadrillion Btu) from direct use (1.1 quadrillion Btu) and indirect use (0.6 quadrillion Btu) is, however, only a small portion ($< 2\%$) of the total energy use in the United States (98 quadrillion Btu). Fertilizers and fuels (diesel and gasoline) account for nearly 65 percent of the energy used in agriculture. Total energy use by agriculture has declined about 30 percent since the 1970s because of the increased use of more fuel-efficient equipment, diesel fuel, and the increased

TABLE 3-3

U.S. farm energy use by source in 2002. *Adapted from Miranowski (2004).*

Source	Percentage of total
Fertilizers	29.0
Diesel	27.3
Electricity	20.7
Gasoline	8.5
Pesticides	6.3
Propane	4.5
Natural gas	3.6

use of conservation tillage. In addition, refinements in fertilizer application practices such as in precision agriculture and fertilizer placement have reduced use while increasing efficiency. The development of biotech crops such as Bt and herbicide tolerance has also decreased use of pesticides. In 2003, energy costs accounted for about 15 percent of the overall production costs in the United States.

Our awareness of energy costs in the United States was greatly increased when crude oil prices and average gas prices rose to all-time highs in 2008. Though we can attribute these increases to many causes, such as refinery shutdowns and politics, they might be best explained by a simple supply-and-demand relationship. The increasing world population and the new industrial development in nations such as China and India have created a huge demand for all fossil fuels. Worldwide energy use is increasing about 2 percent per year, with about 1 percent in North America and 3 percent in Asia. Energy use is not evenly distributed. Though the total world energy use is about 400 quadrillion Btu (70 million Btu per capita), it is 118 quadrillion Btu (280 million Btu per capita) in North America and only about 12 quadrillion Btu (15 million Btu per capita) in Africa. Oil, natural gas, and coal supply more than 85 percent of the energy consumed in the world and the United States (Table 3-4). These fossil fuels are nonrenewable and are not evenly distributed throughout the world. Countries such as the United States that consume a lot but produce very little, must depend on imports from countries such as Saudi Arabia in the Middle East.

Currently, the use of biomass for energy production in the world is limited. In some regions, biomass is used extensively for direct combustion and heating. There is tremendous opportunity to produce products such as ethanol from cellulose and starchy crops or biodiesel to replace our dependence on nonrenewable petroleum. Agriculture will have greater sustainability if the energy from fossil fuels can be conserved.

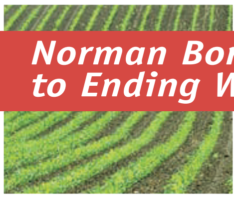
Ecological Footprints and IPAT

An **ecological footprint** is a measurement that represents the combined land and water resources needed to support a human population and to absorb its wastes. Unfortunately, the ecological footprint for the total human population exceeds the

TABLE 3-4

Sources of energy consumption in the world. The energy consumption pattern in the United States is very similar to the world pattern because of its significant energy use. 1 quad = 10^{15} Btu. *United States Geological Survey (2007) and Pimentel et al. (1998).*

Energy type	Quads	World (%)	US (%)
Oil	152	40	39
Natural gas	86	23	23
Coal	89	23	23
Nuclear	25	7	8
Hydroelectric	27	7	4
Biomass	<1	<1	3
Solar	<1	<1	<0.1
Wind	<1	<1	<0.1
Total	425	100	100



Norman Borlaug—A Lifetime Dedicated to Ending World Hunger

Norman Borlaug was a leader of the Green Revolution, which is credited with saving the lives of up to one billion people. Borlaug is one of the most influential alumni from the University of Minnesota (Figure 3-7). He began his career studying forestry, but became interested in plant pathology after hearing a lecture on stem rust by Dr. Elvin Stakman, the head of Plant Pathology. Borlaug went on to get his Masters and PhD degrees in Plant Pathology at the University of Minnesota by 1942.

After obtaining his PhD, Borlaug joined a project with CIMMYT (The International Center for Maize and Wheat Improvement) near Mexico City in 1944 to revitalize Mexico's agricultural practices, especially in regard to wheat, which suffered due to poor soils and an infestation of rust. Borlaug and his colleagues persevered through many hardships in Mexico and, after 10 years, developed wheat varieties that were not only rust-resistant, but also adapted to many climates. This resulted in doubling Mexico's wheat production.

Borlaug wanted wheat varieties that could utilize increased fertilization to improve yields in poor soils; however, at that time, wheat responded to more fertilizer by falling over (lodging), making harvest difficult. Borlaug's solution to the problem was to find a Japanese wheat variety with stronger and shorter stems that also produced multiple seed heads. He crossed this variety with the rust-resistant varieties to create semidwarf varieties. With these semidwarf varieties, along with proper fertilization and



FIGURE 3-7 Norman Borlaug, Nobel Peace Prize winner. He is shown kneeling amongst semidwarf wheat, which he helped develop.

irrigation, Mexico's wheat production increased by six times in volume within the less than 20 years that Borlaug had worked in Mexico. This marked the beginning of the Green Revolution.

The Green Revolution continued in other parts of the world in the late 1960s and 1970s. Borlaug took what he had learned in Mexico and applied it to countries including Pakistan and India. In a few years, the new wheat varieties and production methods increased wheat yields in these countries and reduced the starvation that these populous countries had previously experienced. In 1970, Borlaug won the Nobel Peace Prize for his efforts in India and Pakistan.

Borlaug developed a program in Mexico where agronomists from all around the world could be trained in his techniques in order to take that knowledge back to their home countries. Consequently, this training was able to impact other countries in addition to the ones in which he worked directly. Borlaug had an undeniable influence on the food production systems of the entire world.

Although Borlaug was a major force in agricultural technology improvements worldwide, he realized that technology alone could not solve hunger. He stated in 2004 that "There are two aspects of food and hunger. One is to produce enough food for people in a country and the other is equitability of distribution." Borlaug, who died in 2009, continued his fight against world hunger up to the end of his life at age 95.

earth's ecological carrying capacity by about 25 percent. Some countries such as the United States are using a greater proportion of the earth's resources than others. The ecological footprint for the United States is about 25 acres (10 hectares) per person, whereas in India and many African countries, it is 2.5 acres (1 hectare) or less. It is clear that even with a smaller population, U.S. citizens consume more energy and natural resources, and they produce more waste. For example, the per capita production of carbon dioxide, a greenhouse gas, of developed countries such as the United States averages nearly 14 tons/year (13 metric tons/year), whereas it is only about 3.3 tons/year (3 metric tons/year) for developing countries.

Another way to integrate the multiple factors affecting use of environmental resources is the **IPAT equation**, or $I = P \times A \times T$.

I = environmental impact of resources used and wastes generated

P = size of the human population

A = affluence or level of consumption by a population

T = technology to obtain resources and transform them into useful goods and wastes

Though population numbers have a significant effect on the environment, it is apparent that A and T can also have a large effect. This simple approach, which is used only as a conceptual tool, has been criticized by some experts because of equal weighting of the P, A, and T factors. However, it does serve to outline the important factors impacting our environment.

Increasing World Food Supplies

Can we continue to meet the world's food demands? This is a complex question because of the social and cultural as well as technological factors affecting food production. However, the Green Revolution is an example of the successful application of scientific knowledge of agriculture to solve world hunger problems. **Green Revolution** is a term used to describe activities by scientists at international research centers in improving the production of food crops in developing countries through breeding of new crop varieties and use of production technology such as irrigation, synthetic fertilizer, and pesticides. It has been described as an effort to export temperate-zone agricultural technology to the tropics. Activities associated with the Green Revolution began in the 1940s and are ongoing today.

The Green Revolution is credited with increasing worldwide yields of cereal grains and other important crops. For example, varieties of disease- and lodging-resistant wheat were developed that nearly quadrupled Mexico's wheat production. These improved wheat varieties were later used throughout Latin America and grown in India and Pakistan with similar success. Likewise, new cultivars of rice and corn were developed that significantly improved yields. Norman Borlaug, who received graduate training in plant breeding and pathology at the University of Minnesota, was a leader in the Green Revolution.

Critics of the Green Revolution raised concerns that it had unintended consequences for the developing world. Among the concerns was that the Green Revolution was top-down and tailored for production of specialized varieties that depended on inputs of production variables that only large and rich farmers could afford. The traditional production systems that peasants in some countries used were ignored. As a consequence, although some countries benefited, many like those in Africa did not.

AGRA

The African-led **Alliance for a Green Revolution in Africa (AGRA)** is a dynamic partnership working across the continent to help millions of small-scale farmers and their families lift themselves out of poverty and hunger. Many rural farmers in Africa have for centuries practiced subsistence agriculture. Subsistence farmers have small land areas where they raise food primarily for their own families.

These farms may grow a diversity of crops and have a few livestock. They lack modern inputs and are labor intensive. Subsistence agriculture is often still the best approach to using fragile land that has marginal soil and rainfall for crop production. Conversion of these lands to large-scale industrialized agriculture often results in failure.

AGRA programs develop practical solutions to dramatically boost farm productivity and incomes while safeguarding the environment, culture, and biodiversity. Developing seed, maintaining soil health and water resources, marketing, and agricultural education are emphasized. The Alliance was founded by the Rockefeller Foundation and the Bill and Melinda Gates Foundation in 2006. The goal is that within 10 to 20 years, farmers will double or even triple their yields. This will lead, in turn, to the generation of additional income as farmers sell their surpluses at local and regional markets. This income will help end the hunger and poverty across Africa.

International Research Institutes

The establishment of **international research institutes** throughout the tropical regions of the world was a key component of the Green Revolution. These region-specific institutes enable researchers to focus on improving locally important crops and their production techniques. They also are instrumental in training scientists who return to their countries to share what they have learned. Conserving genetic diversity through maintenance of seed banks is also an important goal of the institutes. The efforts of these institutes are now funded and directed by the **Consultative Group on International Agricultural Research (CGIAR)**, which is a partnership of countries, private foundations, and international organizations (Table 3-5).

TABLE 3-5

Research institutes sponsored by the Consultative Group on International Agricultural Research (CGIAR).

Institute	Location	Major research focus
International Rice Research Institute (IRRI)	Philippines	Rice
Centro Internacional de Mejoramiento de Maiz y Trigo (CIMMYT)	Mexico	Wheat, corn, triticale
Centro Internacional de Agricultura Tropical (CIAT)	Colombia	Beans, cassava
International Institute of Tropical Agriculture (IITA)	Nigeria	Legumes, roots, tubers
West Africa Rice Development Association (WARDA)	Côte d'Ivoire	Rice
Centro Internacional de la Papa (CIP)	Peru	Potato
International Crops Research Institute for Semi-Arid Tropics (ICRISAT)	India	Sorghum, millet, legumes
International Center for Agricultural Research in Dry Areas (ICARDA)	Syria	Barley
International Irrigation Management Institute (IIMI)	Sri Lanka	Irrigation
International Council for Research on Agroforestry (ICRAF)	Kenya	Agroforestry
International Livestock Center for Africa (ILCA)	Ethiopia	Cattle, sheep
International Board for Plant Genetic Resources (IBPGR)	Rome	Gene conservation

Solutions

In this text, we reviewed crop production processes in the United States that have resulted in a bountiful and low-cost food supply. We have benefited from ingenuity and abundant natural resources. Expanding world populations will likely test the earth's carrying capacity, and a worldwide crisis may occur that will significantly reduce the population. Overall, a sustainable agricultural production system needs to be implemented that considers the environment, food production, economics, and culture. A sustainable agriculture will include the following objectives:

- *Preserve existing land.* Strategies need to be devised to protect existing land used for crop and animal production. These include conservation tillage, crop rotation, and strategic crop placement on landscapes. Irrigation strategies need to be developed to increase its efficiency and to reduce the incidence of salinization. Rural landscapes should be viewed as producers of multiple benefits: economical as well as ecological. Although increased use of land will put pressure on remaining natural ecosystems, thoughtful planning is required to balance preservation with exploitation.
- *Practice water conservation.* There is little chance of opening up new sources of water, so sustainable water use of existing resources must be implemented. Farming practices such as increasing the amount of cover on the soil surface (using cover crops, mulches), installing high-efficiency drip irrigation, utilizing demand-based irrigation schedules, planting drought-tolerant crops, and protecting soil resources all minimize water loss and enhance infiltration of precipitation. Other land management and planting practices that minimize runoff and water loss include protecting and maintaining natural networks of water purification (wetlands, marshes) and lands that protect soil from erosion.
- *Develop other approaches to crop production.* Although modern industrialized, high-input agriculture has worked exceptionally well in the United States, its application throughout the world has not always been successful. Alternative approaches to crop production such as organic farming that minimize inputs and fit local environmental limitations need to be expanded. In many regions of the world, the small-scale family farm may be the best way to promote a sustainable agriculture.
- *Increase funding for agricultural research.* We should continue plant-breeding and genetic-engineering research that is aimed at increasing the efficiency of crop productions (e.g., increased water-use or plant-nutrient-use efficiency) and the quality of the product while conserving genetic diversity through preservation of local, indigenous plant materials. It will be important to develop crops that fit local crop production systems. In the future, we will need crops that can use marginal soils that have been compromised by salinization, acidity, or organic matter loss.
- *Maintain genetic diversity.* We need to preserve genetic diversity of existing crops in seed banks and search for new crops that might produce food, fuel, or medicines in unique environments.

- *Reduce fossil fuel reliance*. We should expand the use of crops for production of renewable energy to reduce the world's growing dependence on fossil fuels. Starchy grains such as corn may provide a feedstock for a limited amount of biofuel, but their use as a human and livestock feed should be given a higher priority. Dedicated cellulosic ethanol crops such as switchgrass in the United States or sugarcane in Brazil appear to be more sustainable fuel sources.

Review Questions

1. What is the population in the world today? What is the relative population growth in developing and developed countries of the world?
2. Has the world been able to supply the food it needs for itself? How has it, or how has it not?
3. Many people in the world do not have adequate nutrition. Why?
4. How is poverty related to the supply of food?
5. What are some of the ways in which soil is degraded or lost?
6. About how much of the world's fresh water is used in irrigation?
7. What is the Ogallala aquifer? How is it used, and what are the environmental consequences of its use?
8. What are the sources of energy used in the world today? How is energy used in agriculture?
9. What is the ecological footprint?
10. Discuss each component in IPAT.
11. Describe the Green Revolution and discuss its benefits and shortcomings.
12. Discuss several strategies for meeting future food needs.

Critical Thinking

1. Conduct a Web search and identify the activities of one of the CGIAR international research centers.
2. Using a search engine, go to a website that enables you to determine your own ecological footprint, for example, http://www.footprintnetwork.org/ Accessed 17 June 2010.
3. Do you think that agricultural technology will be able to increase fast enough with population growth to prevent famine? Why or why not?
4. If you were a leader of the United Nations and had the opportunity to abolish world hunger, what strategies would you use?
5. Read Norman Borlaug's Nobel Prize acceptance speech (http://nobelprize.org/). Write a paragraph describing your response to the speech.

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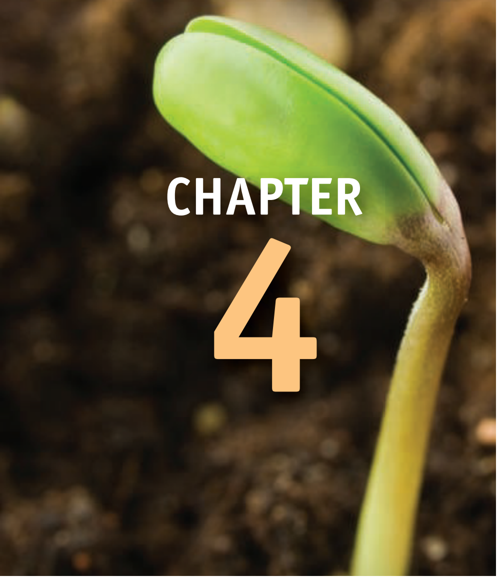
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CHAPTER 4



Classifying and Naming Crops





Key Concepts

- Crops can be classified by agronomic use, nutritional use, life cycle, and climate adaptation.
- Agronomic crops include cereals, grains, pulses, forages, fiber crops, cover crops, companion crops, green manure crops, and recreational turf crops.
- Bioenergy can be produced from grain crops, forage crops, and oil crops.
- Nutritional-use classification includes sugar crops, oil crops, protein crops, starchy seed crops, and root and tuber crops.
- Crops can be grown for medicinal purposes.
- Many plants are toxic, or even deadly, to people and livestock.
- Plants are scientifically described using two-part scientific names: the genus and species.
- Taxonomy is a system of organizing plants into species, families, orders, classes, and divisions.

Key Terms

bioenergy
biofuel
biomass
cereal crop
companion crop
cover crop
dicot
fiber crop
forage
grain crop
genus
green manure crop
hay
monocot
oil crop
protein crop
pulses
root crop
scientific name
silage
small grain
species
taxonomy
tuber crop

Introduction

Agronomy is the production of field crops while sustaining the soil resource and the environment. The word *agronomy* comes from the Greek words *agros* (field) and *nomos* (to manage). Most field crops are ultimately used for food production, but they have other important uses. To facilitate their description, we place crops in categories based on their agronomic, industrial, and nutritional uses. Categorization involves the use of professional and technical terminology. An aspect of categorizing crops is naming them. All crops have a common name and a two-word scientific name. Profiles of individual crops are provided in Chapters 19, 20, and 21.

Agronomic Crop Categories

This category includes cereals, grains, pulses, forages, fiber crops, root and tuber crops, cover crops, companion crops, green manure crops, and recreational turf crops.

Cereal Crops

Cereal crops are grasses that produce edible grain. The word *cereal* is derived from the name of the Roman goddess of grain, Ceres. Wheat, rice, corn, barley, and sorghum are the most important cereal crops grown in the world today. Cereals store energy in their seeds as starch. The starch can be extracted from the grain and used as an energy source for livestock and humans. Cereal grains contain about 75 percent starch, 12 percent protein, 2 percent fat, and smaller quantities of vitamins and minerals.

A popular American definition of a cereal is that cereals are processed breakfast foods to which milk is added (Figure 4-1). Today, manufacturers make numerous



Scott Bauer, USDA-ARS.

FIGURE 4-1 A bowl of cereal is a common breakfast today due to the influence of the Kellogg brothers from Battlecreek, MI.

processed breakfast cereals from corn, wheat, rice, and oats, and these cereals are marketed to children and adults. Around 1900, William and Harvey Kellogg developed the original breakfast cereals in Battle Creek, Michigan. They developed their first products, corn flakes and shredded wheat, as low fat and fibrous health foods. Today's breakfast cereals vary greatly in nutritional content and potential health benefits.

Grain Crops

Grain is the fruit or seed of a crop plant. Similar in definition to cereal crops, the term **grain crop** is applied to the harvested portion of a number of grass crops such as corn. But the term also includes legumes such as soybean and kidney beans, and other plants such as flax and buckwheat. **Small grain** is a term applied to wheat, oat, barley, and rye because, relative to corn, their seed is small.

Pulses

Legumes grown for their edible, high protein seeds are known as **pulses**. Pulses contain up to a third of their dry weight in protein. They store energy as carbohydrates or oil. Pulse seeds are borne in pods that burst into halves when mature and dried. Pulse crops include soybeans, edible field beans, field peas, lentils, peanuts, chickpeas, and cow peas. Most pulses should be roasted or boiled before human consumption to destroy chemicals that reduce the availability of nutrients. Many pulses such as field beans, chickpeas, field peas, and lupines are important components of human diets. Soybean is the most widely grown pulse (Figure 4-2). Humans consume the soybean itself in the form of soy paste (miso) and soy curd (tofu), and we eat it as a germinated seed (bean sprouts). Its oil (soybean has an oil content around 13–25%) is extracted and used for cooking, and farmers use the protein-rich meal for livestock feed.



Scott Bauer, USDA-ARS.

FIGURE 4-2
Soybeans are a pulse crop used as an ingredient in many foods.

Forages

Forages are any crops whose vegetative parts—including stems, leaves, and sometimes attached seed or grain—are used for livestock feed. Animals can take forages directly from pastures by grazing, or forages can be fed following storage (Figure 4-3). Grazing is the most traditional form of forage use, and "free ranging" of livestock was a common practice during the European settlement of North America. Grazing is important today in permanent pastures, rangelands, and cropland pastures. In many regions, pasturing is restricted for many months of the year due to cold weather or drought, and stored forages are critical to meet animals' needs. Farmers store forages as hay or silage. **Hay** is forage that is dried to about 20 percent moisture and stored in the air, whereas **silage** is harvested at 50–80 percent moisture and sealed in a structure called a silo. Forages are also important in crop rotations and are often grown on erodible lands unsuitable for tillage.

Forages are natural feeds for ruminant animals and wildlife. Ruminants such as sheep, goats, cattle, and deer are capable of digesting fibrous portions of plants and can use many plant materials that humans cannot digest. Ruminants are a unique complementary meat and protein source for humans who depend on grains to supply energy nutrition. In modern meat production systems, many livestock are fed a combination of forages and grains to achieve high levels of meat or milk production. Producers grow a diversity of perennial and annual plants for forage. Species used depend on the climatic and soil conditions and the intended use.

- In the northern United States and Canada, temperate cool-season legumes such as alfalfa and clovers, and grasses such as smooth bromegrass and timothy, are used for pasture, hay, and silage.



Craig Sheaffer.

FIGURE 4-3 Horses foraging on a pasture.

- In the southern United States, annual clovers, bermuda grass, and tall fescue are grazed and used for hay.
- In the dryer regions of the Great Plains, shrubs and native grasses such as big bluestem, little bluestem and buffalo grass are grazed.
- Throughout the United States, corn and small grains are harvested for silage when they are immature. In some regions, small grains are grazed.

Fiber Crops

We use fiber from plants for clothing, rope, paper, and baskets. This fiber is a collection of individual fiber cells as described in Chapter 8. Cotton, flax, hemp, and ramie are **fiber crops** that each produce fiber of different characteristics.

Cotton fiber is mostly pure cellulose and is white. It is called a surface fiber and surrounds the seed. Cotton fibers vary in length and are twisted. Cotton is the most widely used natural fiber crop.

Flax fiber is called bast fiber, which is the soft fiber extracted from the stem. The cloth produced after processing is called linen. Flax is the oldest crop used for fiber and cloth production. Flax fibers are longer than those of cotton and average about 2 feet in length. They consist of about 70 percent cellulose with some waxes mixed in.

Hemp fiber is also extracted from the stem. It is very coarse and brown. It is an extremely strong fiber used for the production of canvas, rope, and bags. Hemp is illegal to grow in the United States, but the fiber can be imported.

Ramie is one of the oldest fiber crops. Its bast fibers are harvested from the bark of the plant. Unlike many other fiber crops, ramie is a perennial species that can be harvested several times a year for up to 20 years.

Root and Tuber Crops

White or Irish potatoes, sweet potatoes, and cassava are examples of **root crops**, or **tuber crops**. They are harvested for their underground storage organs that are rich in starch. Potatoes are enlarged underground stems called tubers. Though sweet potatoes and cassava seem similar to the Irish potato, they have enlarged roots, not tubers. These crops are among the most important in the world as a source of energy for human nutrition. Another tuber-producing crop is Jerusalem artichoke. In contrast to Irish potatoes, Jerusalem artichokes store energy as inulin, another type of complex carbohydrate.

Cover Crops

Farmers use **cover crops** to prevent soil erosion due to water or wind during periods when the soil is not protected by growing plant cover. For example, in the Midwest, summer annuals such as corn and soybean are normally in the field from May through October. The soil remains uncovered, except for crop residue, from November until the following spring. A cover crop such as winter rye or hairy vetch is sometimes planted in late fall to provide soil cover over the winter.

Companion Crops

Companion crops such as oat and wheat have traditionally been seeded with a small-seeded legume such as alfalfa to provide erosion control, suppress weeds, and provide some income from the land during the establishment period if either crop fails (Figure 4-4). Companion crops are harvested at maturity for grain and straw or when immature for silage. Following the harvest of the companion crop, the legume will regrow.

Green Manure Crops

Green manure crops are legumes or grasses that are incorporated into the soil while vegetative with the purpose of adding nutrients to the soil or enhancing soil quality. Sweet clover is an example of a traditional green manure crop that farmers grow expressly for the purpose of plowing down and adding nitrogen and organic matter to the soil. Other examples include alfalfa (Figure 4-5), hairy vetch, crimson clover, and winter rye.

Recreational Turf Crops

Many perennial grasses such as Kentucky bluegrass, perennial ryegrass, and bent-grass are used for recreational purposes. Kentucky bluegrass and ryegrass are used extensively for lawns, soccer fields, and football fields in the northern regions of the United States. Further south, bermuda grass is often used in recreational areas such as golf courses (Figure 4-6). Varieties of these species have been selected with tolerance to wear from human traffic.



Craig Sheaffer.

FIGURE 4-4
An oat companion crop grown with alfalfa.



David L. Hansen, University of Minnesota.

FIGURE 4-5
Alfalfa can be used as a forage crop, companion crop, or green manure.



Wayne Hanna, USDA-ARS.

FIGURE 4-6
Closely-mown bermudagrass golf green at a Savannah, Georgia, course. Bermuda grass is a tropical species adapted to the southern United States.

Bioenergy Crops

Bioenergy is a general term that describes production of energy from biological systems. We also use the terms *biomass* and *biofuel* to describe bioenergy. **Biomass** crops are burned to produce heat and electricity. Biomass crops include trees such as hybrid poplars and willows, or herbaceous perennials such as switchgrass or alfalfa. **Biofuel** crops are crops grown specifically for use as a dedicated fuel source for production of liquid fuels. Corn, grain sorghum, and soybean are examples of biofuel crops. Starch in the grain of corn and to a lesser extent sorghum is converted to ethanol, while oils from soybean are converted to biodiesel.

Nutritional-Use Categories

Crops can be classified by the way we use them nutritionally. The basic components of human and animal diets are fats, proteins, and carbohydrates such as sugars and starches (see Chapter 5).

Sugar Crops

Sugar beets, sugarcane, corn, and sweet sorghum are some of the crops from which sugar is obtained. The sugar beet is a root crop grown for sucrose. Sugarcane stores sugar in a tall-growing stem that is crushed during sugar extraction. Corn is the source of high fructose corn syrup, which is the leading sweetener used in drinks and candies. It is produced by conversion of corn starch from the kernel to a fructose-glucose mixture. Sweet sorghum, which is related to grain sorghum, is another tall-growing plant where the stem is pressed to extract sugars to produce syrup. Sweet sorghum acreage in the United States is low (less than 30,000 acres).

Oil Crops

Many crop species produce oil-rich seeds that can be processed for their oil. **Oil crops** produce oils that contain fatty acids that vary in saturation. Oil crops include soybean, flax, sunflowers, canola, peanuts, and cotton. Soybean accounts for half of edible oil production.

Protein Crops

Legumes such as soybean, peas, field beans, and peanuts produce seeds that are naturally high in protein. These **protein crops** are an important source of protein in many parts of the world. Nonlegumes can also be used for seed protein production and include quinoa, cotton, and sunflowers.

Starchy Seed Crops

Seed from the cereal grasses is naturally high in starch. Cereal crops include corn, wheat, oat, barley, rye, millet, and sorghum. Nongrasses such as amaranth and buckwheat also produce starchy seed.

Starchy Root and Tuber Crops

Roots and tuber crops store their energy primarily as starch. Humans can convert this starch to energy.

Medicinal and Psychoactive Crops

Plants contain many unique substances that humans utilize in ways other than for nutrition. Medicinal and psychoactive crops are grown for their unique compounds such as alkaloids and glycosides that have properties for pain relief, hallucinogenic effects, disease treatment, or other uses. Medicinal plants include aspirin from willows, quinine from the fever bark tree, and vinicristine from Madagascar periwinkle (Table 4-1). Almost half of all drugs used today came originally from plants. However, many medicines are no longer derived directly from the plants in which they were discovered; once the active compounds are isolated and synthesized, they can be produced in laboratories. Plants will continue to be a source for drugs as researchers hunt for new compounds that may yield the next new drug.

TABLE 4-1

Medicinal plants. *Adapted from Levetin and McMahon (1996).*

Plant	Active compound(s)	Medicinal use
Aloe vera	Aloin	Burns
Madagascar periwinkle	Vinblastine, vincristine	Leukemia, lymphoma
Fever bark tree	Quinine	Malaria
Purple foxglove	Digitoxin	Congestive heart failure
Eucalyptus	Eucalyptol	Cough suppressant
Opium poppy	Morphine, codeine	Pain
White willow	Salicin	Pain, fever
Pacific yew	Taxol	Cancer
Mayapple	Podophyllotoxin	Cancer

TABLE 4-2

Psychoactive plants. *Adapted from Levetin and McMahon (1996).*

Plant	Active compound(s)	Effect
Opium poppy	Morphine, codeine	Depressant
Marijuana	Tetrahydrocannabinal	Hallucinogen
Coca	Cocaine	Stimulant
Tobacco	Nicotine	Stimulant/depressant
Coffee	Caffeine	Stimulant
Tea	Caffeine	Stimulant
Peyote	Mescaline	Hallucinogen
Salvia	Salvinorum A	Hallucinogen

Some of the more common psychoactive crops include tobacco, opium poppy, coca plant, and marijuana (Table 4-2). Tobacco is cultivated in the United States, the opium poppy in Afghanistan, and the coca plant in the Andes countries of South America. Products derived from these plants can lead to human addiction and can exact a significant toll on human health and society. Costs related to extra health care and law enforcement for nonalcohol-related substance abuse is a staggering $250 billion dollars per year. Tobacco use is legalized, but smoking and chewing tobacco cause cancer and cardiac and respiratory problems. However, in addition to direct health impacts, the illegal trade and use of other drugs like opium and heroin, derived from the opium poppy, and cocaine, derived from the coca plant, are a leading cause of gang warfare and societal breakdown in the United States and supplying countries.

Psychoactive crops can also be valued as medicines. For example, morphine also is produced from the opium poppy and is prescribed to relieve extreme pain resulting from injury, surgery, or cancer. Marijuana is considered an illegal hallucinogenic drug in most of the United States, but it can also be used legitimately to treat diseases such as glaucoma in 14 U.S. states.

Toxic Plants

Most of the plants described in this chapter demonstrate the benefits that plants provide people, yet many other plants are harmful or even deadly. A common garden plant, monkshood, contains an alkaloid called aconitine that, in high doses, causes death by heart failure or asphyxiation. This plant is so toxic that it should not be allowed to touch bare skin as it can be absorbed through the skin and reach the circulatory system. During WWII, German Nazis used aconitine in poison bullets.

Medicinal Plants in Your Backyard

Where will the next new drug to fight cancer or to fight antibiotic-resistant bacteria come from? Humans have historically had a connection to the plants in their surroundings. Originally, based on trial and error, and now systematically, humans have sought out and used plants for medicinal purposes. In fact, the study of medicinal products from plant sources is called *pharmacognosy*. Today, while many of the drugs we use are chemically synthesized and have replaced plant sources, the search for new medicines from plants continues.

A striking example of a plant that has saved many human lives and ended the lives of many rodents is sweet clover. In the 1940s, Dr. Karl Link, a biochemist at the University of Wisconsin, identified dicoumarol, a hemorrhagic (bleeding) agent from moldy, sweet clover hay. Sweet clover is a tall-growing, sweet-smelling, legume that was once widely used as a forage crop (Figure 4-7). Unfortunately, sweet clover is very succulent, and hay made from sweet clover often molds. Cattle consuming moldy sweet clover suffered from "bleeding disease," or uncontrolled bleeding, and often died. Chemically, dicoumarol, formed by fungal growth from the precursor chemical coumarin, prevents the formation of prothrombin by interfering with Vitamin K activity. Today, synthetic versions of the compounds are used in Coumadin®, a blood thinner for treating cardiovascular disease. Paradoxically, it is also used to form warfarin, a widely used pesticide to control rat and mice pests.

Research on finding new medicinal plants is ongoing. There is a great need for new antimicrobial agents to fight drug-resistant microorganisms and to act as natural preservatives in foods and cosmetics. Researchers at the University of Minnesota are currently searching for phytochemicals in seed and foliage of native and naturalized plants. They collected samples from over 300 plant species and analyzed them for activity against *Staphylococcus aureus* (*Staph* bacterium)



David L. Hansen, University of Minnesota.

FIGURE 4-7
Yellow sweet clover.

(*Continued*)

Escherichia coli (*E. coli* bacterium), *Pseudomonas aeruginosa* (a bacterium), and *Candida albicans* (a yeast). They reported that extracts of leaves and flowering parts of smooth sumac, fireweed, St. John's wort, spotted knapweed, and purple loosestrife inhibited growth of all four organisms. Not surprisingly, several of these plants have long been used in Native American medicine (Borchardt et al., 2008). This work, while of interest, is still preliminary as several more steps are required to develop a new plant-derived drug. The next step is to isolate and identify potentially active compounds that induce the antimicrobial effect. Further along in the process, the optimum rate for usage must be determined and clinical trials must be conducted. The failure rate is high in drug research and most compounds are deemed unsuccessful before even reaching clinical trials.



Brian Prechtel, USDA-ARS.

FIGURE 4-8 Castor beans. A human can die after ingesting only three beans.

Castor bean is a tropical plant grown commercially for production of castor oil, an industrial lubricant, but has also been introduced into North America and used as an ornamental plant. The foliage and attractive large beans (Figure 4-8) contain ricin, which interferes with protein synthesis in humans and animals. Ingestion of seeds can be fatal as there is no known antidote. Ricin has been investigated as a biological warfare agent, used for political assassination, and has been seized from extremist groups that apparently intended to use it for nefarious, socially disruptive activities. Ricin is extracted from the seed during oil production.



FIGURE 4-9
White snakeroot blooms in the fall and can be found in the eastern half of the United States and Canada.

Jimson weed has an interesting history dating back to the early colonists. In their search for food sources during severe food deprivation in the early 1600s, Jamestown settlers learned that the seeds of this weed were toxic. Years later, during the Revolutionary War, colonists used jimson weed to poison the food of British soldiers with whom they were battling. The soldiers were incapacitated by the psychosis and hallucinations. Jimson weed was once known as Jamestown weed, named after the Jamestown settlers.

White snakeroot is a plant that plagued settlers in the northern United States in the 1800s (Figure 4-9). It was found in association with newly cleared forests and woodlands, and free-ranging livestock frequently consumed it. At this time, it was common for farm families to own a few cows for milk production and cheese making. Humans who drank the milk or ate the meat from affected cattle developed milk sickness. The fat-soluble compound, tremetol, that was passed through to the milk caused weakness, tremors, delirium, and death for both humans and livestock. One reported famous victim of milk sickness was the mother of Abraham Lincoln (Miller, 2006). It was not until the early 1900s that white snakeroot was identified as the causal agent of milk sickness.

Poisons found in plants have been utilized as weapons by tribes in South America. Indigenous people coated the tips of arrows with a poison called *curare*, found in the curare vine that is common throughout South America. Prey hit by a poison arrow become paralyzed, allowing for easy capture. Animals caught using this technique are still safe to eat because the alkaloid must be injected into the bloodstream in order to cause symptoms. See Table 4-3 for examples of toxic plants.

TABLE 4-3

Plants toxic to humans. *Adapted from Levetin and McMahon (1996) and Stewart (2009).*

Plant	Active compound(s)	Effect
White snakeroot	Tremetol	Tremors, delirium, death
Water hemlock	Cicutoxin	Convulsions, death
Tobacco	Nicotine	Cramps, seizures, death
Strychnine tree	Strychnine	Seizures, respiratory failure, death
Poison ivy	Urushiol	Oozing rash
Poison hemlock	Coniceine	Paralysis, death
Oleander	Oleandrin	Weakness, death
Monkshood	Aconitine	Paralysis, death
Jimsonweed	Tropane alkaloids	Seizures, hallucinations
Death camas	Zygacine	Weakness, seizures, death
Deadly nightshade	Atropine	Psychosis, seizures, death
Castor bean	Ricin	Hemorrhages, death

Naming Plants

Every culture has given plants common names that often describe a morphological feature or a use. For example, white clover is a legume plant with white flowers, whereas red clover is a legume with red flowers. Also, white snakeroot, a poisonous plant described in this chapter, is so named because of its white flowers and roots that grow from the crown in a snake-like fashion. The challenge with common names for plants is that they vary regionally and nationally. In Europe, for instance, alfalfa is also known as lucerne, corn is known as maize, and wheat is known as corn. Orchardgrass, a forage grass in North America, is called cocksfoot in Europe.

Scientific Names

Scientific names allow for the universal identification of plants. In the eighteenth century, the Swedish botanist Carolus Linnaeus first developed the binomial nomenclature system of plant identification. In the binomial system, plants are identified using a two-part Latin name: the **genus** and **species**. Scientific names are always italicized, with the genus capitalized. Each unique plant is called a species, and similar species form a genus. A complete scientific name also includes the name(s) or abbreviation of the name of the individual(s) who first described the species. For example, the complete scientific name for soybean is *Glycine max* L. with *L.* being an abbreviation for Linnaeus, who named this species. Species that have been subject to plant breeding and selection can be identified as a variety,

cultivar (short for cultivated variety), or hybrid number. See Appendix 1 for a listing of common and scientific names.

Taxonomy

Taxonomy is a system of organizing all life based on similar genetic or morphological characteristics. Species are the lowest taxonomic unit. Similar species are grouped into families, families into orders, orders into classes, classes into divisions, and divisions into kingdoms. The kingdom category separates plants from animals. See Table 4-4 for an example of the complete classification for corn (a grass) and soybean (a legume). For comparison, the taxonomy of a cow is provided. Two categories particularly relevant to plants are classes and families.

Dicots and Monocots

Crop plants can be classified as dicots or monocots. **Dicots** are plants such as soybeans and sunflowers that have two seed leaves (cotyledons) within the seed. **Monocots** are plants such as corn and bluegrass that have a single cotyledon within the seed. Dicots and monocots also differ in root, stem, leaf, and flower characteristics (see Chapter 7).

Plant Families

Plant genera are grouped into families based on floral, fruit, or genetic characteristics. The families of some important crops and crop weeds are shown in Table 4-5. Two of the most important crop families—with a large number of species of economic significance—are the Poaceae (grass) and Fabaceae (legume) families. Note that family names end in the suffix *-aceae*.

TABLE 4-4

Complete classification of corn, soybean, and cow. The division Magnoliophyta includes the flowering plants. The class Liliopsida represents monocot plants, and Magnoliopsida represents dicot plants. The family Poaceae is the grass family, and Fabaceae is the legume family. *USDA-NRCS (2007)*.

	Corn	Soybean	Cow
Kingdom	Plant	Plant	Animal
Division	Magnoliophyta	Magnoliophyta	Chordata
Class	Liliopsida	Magnoliopsida	Mammalia
Order	Cyperales	Fabales	Artiodactyla
Family	Poaceae	Fabaceae	Bovidae
Genus	*Zea*	*Glycine*	*Bos*
Species	*mays*	*max*	*tarus*

TABLE 4-5

Important families of crop and weed plants, and their characteristics.

Monocot families	Crops	Weeds	Characteristics
Poaceae (Grass family)	Barley, Corn, Oat, Wheat, Rice, Sugarcane	Foxtail spp., Fall panicum, Quackgrass, Cheatgrass	Includes about 600 genera and 9000 spp. Most widely distributed. Highly specialized leaves, stems, and flowers. Mostly hollow stems (culms).
Cyperaceae (Sedge family)	Water chestnut	Nutsedge spp.	Solid, triangular stems. Leaves three-ranked.
Dicot families	**Crops**	**Weeds**	**Characteristics**
Fabaceae (Legume family)	Soybean, Peanut, Pea, Vetches, Alfalfa, Clovers	Black medic, Kudzu, Wild licorice	Includes 630 genera and 18,000 spp. Seeds borne in pods. Conduct biological N_2 fixation. Seeds and vegetation rich in protein.
Solanaceae (Nightshade family)	Potato, Tomato, Tobacco, Pepper	Nightshade, Jimsonweed	Includes 85 genera and 2800 spp. Contains alkaloids.
Convolvulaceae (Morning-glory family)	Sweet potato	Field bindweed, Dodder	Viny herbage. Leaves frequently heart- or arrow-shaped.
Asteraceae (Sunflower family)	Sunflower, Artichoke	Dandelion, Thistle, Ragweed	Largest family with 1100 genera and 20,000 spp. Head inflorescences.
Chenopodiaceae (Goosefoot family)	Sugar beet, Quinoa, Spinach	Lambsquarters, Kochia, Russian thistle	Taprooted succulent annuals. Leaves of some species shaped like goosefoot. Flowers small and greenish.
Amaranthaceae (Amaranth family)	Amaranth	Pigweed, Waterhemp	Taprooted herb. Very small flowers.
Polygonaceae (Buckwheat family)	Buckwheat, Rhubarb	Smartweed, Knotweed	Pungent acid juice in stem.
Linaceae (Flax family)	Flax		Annual with fibrous stem.
Brassicaceae (Mustard family)	Canola, Mustard, Turnip	Garlic mustard, Shepardspurse	Many winter annuals and biennials. Herbage and roots often produce pungent odor. Petals often form cross.
Cucurbitaceae (Squash family)	Squash, Cantaloupe, Pumpkin		Includes 90 genera and 700 annual spp. Viny crops with large, fleshy fruits. Large, bright flowers often unisexual.
Malvaceae (Mallow family)	Cotton, Okra	Velvetleaf, Mallow	Includes 204 genera and 2300 spp. Have mucilaginous sap.

The Nightshade Family

The Nightshade family (Solanaceae) is one of the most interesting plant families when it comes to food, medicines, drugs, and toxic compounds (Figures 4-10 and 4-11). It is a family of extremes when it comes to human usage. It contains plants that are extremely nutritious, plants that upon ingestion can easily kill people, plants that can be used in weapons, and one plant that is responsible for the deaths of millions of people each year. Here is a listing of some of the more significant plant species that belong to this family.



FIGURE 4-10
Potato flower. Members of the Solanaceae family generally have flowers with five petals, often fused.

Keith Weller, USDA-ARS.



FIGURE 4-11
Tomato fruit. Berries (the fruit of the tomato) are a common characteristic of the Solanaceae family.

Peggy Greb, USDA-ARS.

(*Continued*)

- Crops species: Potato, tomato, pepper, eggplant, huckleberry, and goji berry. The most significant economically is the potato, the fourth most important crop in the world. One interesting fact about tomatoes: when they were brought to the Old World, Europeans were slow to embrace the delicious fruit. They were well aware that it belonged to the Solanaceae family and thought they could be poisonous.
- Weed species: Eastern black nightshade, jimsonweed, and buffalo bur. These are weeds from the Solanaceae family that affect agronomic crops.
- Ornamental species: Moonflower (*Datura* species), flowering tobacco (*Nicotiana* species), and petunia. Petunias are among the most popular bedding plants.
- Weapon species: Chili pepper. Some varieties of chili peppers are used as components in pepper spray that is used for self-defense.
- Medicinal species: Deadly nightshade, mandrake, chili pepper. Deadly nightshade and mandrake contain atropine, a muscle relaxant and antidote to nerve-gas poisoning. A compound in chili pepper called *capsaicin* is used in topical creams.
- Insecticide species: Tobacco. Nicotine, the addictive ingredient in tobacco-based products, causes convulsions and death in insects upon contact. Synthetic derivatives of nicotine used for insecticides include imidacloprid, thiacloprid, acetamiprid, and thiamethoxam.
- Poisonous species: Mandrake, deadly nightshade, henbane, jimsonweed, tobacco. Ingestion of either the herbage, berries, or seed of these species can lead to death. Even contact with the skin can cause a reaction. Tobacco through smoking cigarettes causes cancer and other ailments and kills five million people a year. By 2020, this number is expected to rise to 10 million people a year.

What makes this plant family so special? Part of the explanation is due to particular compounds produced by members of Solanaceae (and in some other plant families) called *alkaloids*. Alkaloids are nitrogen compounds that cause physiological effects in humans. One of the most well known of these alkaloids is nicotine, which is the major alkaloid found in tobacco (Figure 4-12). Nicotine acts on the central nervous system by releasing adrenaline, slowing the heart rate, and raising blood pressure. Nicotine is also highly addictive.

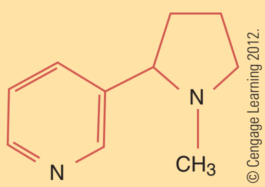


FIGURE 4-12
The chemical structure of nicotine.

Another common group of alkaloids found in the Solanaceae family are the tropane alkaloids. Tropane alkaloids, which include atropine, hyoscyamine, and scopolamine, are extremely toxic and, in high enough doses, can induce coma or respiratory arrest and death. In nonlethal doses, tropane alkaloids have a wide range of effects on the body, including relaxing of smooth muscles, dilation of pupils, dilation of blood vessels, increased heart rate and body temperature, induction of sleep, and decrease in pain. One of the plants with the tropane alkaloids is deadly nightshade, which has a long history of poisoning. Deadly nightshade contains the alkaloid atropine, which causes a rapid heartbeat, confusion, hallucinations, and seizures.

A different intriguing compound that is not an aklaloid is capsaicin, found in chili peppers. Capsaicin is the chemical responsible for the heat of peppers. Some chili peppers are so high in capsaicin that they are used as a component in pepper sprays. At high enough levels, capsaicin can cause enough agony to send a person to the hospital or even cause death. Capsaicin has medicinal uses, too. It is used in topical creams that treat arthritis and back pain.

Review Questions

1. Define and give examples of these agronomic crop categories: forages, pulses, root crops.
2. Provide two separate definitions of the term *cereal*. One should be an agronomic definition, the other a common-use definition.
3. Define and give an example of the following nutritional crop-use categories: sugar crops, oil crops, protein crops, and starchy seed crops.
4. What is the difference between a medicinal and psychoactive crop?
5. Describe one plant toxic to humans, its active component, and its effect on the human body.
6. What is plant taxonomy?
7. Give the scientific name of a commonly grown crop plant.

Critical Thinking

1. Soybean can be categorized as a fuel crop, a pulse, a grain crop, a protein crop and an oil crop. How many ways can you think of to categorize corn?
2. Would you ever be tempted to eat a plant found in the wild? Why or why not?
3. Review the common and scientific names of a crop plant that you choose. Much of our English language is based on Latin. Can you interpret the Latin name?

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CHAPTER 5



Food and Energy from Plants





Key Concepts

- All our food, directly or indirectly, comes from plants. Macronutrients include carbohydrates, proteins, lipids, and water.
- Micronutrients include vitamins and minerals.
- To be healthy, humans need to derive the proper amounts of macronutrients as well as micronutrients from their diets.
- In the past century, American diets have changed regarding the types of food and the amount of food we eat.
- Food availability and food cost affect what we eat and are influenced by challenges associated with crop production.
- The energy stored in crop grains and in leaf and stem cellulose can be converted to biofuels.
- Corn is the leading crop used for ethanol production.

Key Terms

body mass index (BMI)
calorie
dietary reference intakes (DRI)
distillers grains
enriched
Food Guide Pyramid
macronutrient
malnutrition
micronutrient
nutrition
obesity
refining
undernutrition
whole grain

Introduction

Food provides nutrition and is essential for human survival. In the history of human societies, food procurement either by hunting and gathering or by the gardening of domesticated plants has been a necessary preoccupation. In this era of food abundance and fast foods, we often take food availability for granted. All food directly or indirectly comes from plants that capture the sun's energy. Through the process of photosynthesis, plants convert this energy into a form humans and animals can use. Meat, milk, and eggs come from animals that have consumed grain or herbage produced by plants. Because many foods today are highly processed for quick preparation, we lose sight of their origins. Recently, people in the United States have focused their attention on producing healthy foods and on the various problems associated with the excess consumption of food.

Food also has a major social significance. Our social relationships are characterized by the type of eating we do, whether it is in the form of a business lunch, coffee with old friends, a romantic candlelight dinner, or family gatherings on national or religious holidays. Saying that you are "breaking bread" with someone has historically meant some level of trust exists among the people involved, whether they are friends or even enemies. Within daily family activities, traditional mealtimes like breakfast, lunch, and dinner have provided an opportunity for familial interactions. Recent alterations in the eating patterns of households brought about by busy schedules and changing family structures have changed the nature of that interaction.

Human Nutrition

Nutrition is broadly defined as the complex interaction of humans with food. It involves not only biochemical processes but also those social, economic, and physiological factors that describe why we eat what we eat. Carbohydrates, proteins, lipids, and water are **macronutrients** and are consumed in large quantities, whereas vitamins and minerals are classified as **micronutrients** that are required in small quantities. The properties of these macronutrients and micronutrients and their composition are described in more detail in Chapter 6. Nutrients from plant and animal sources consumed by humans are used for energy, structure, and metabolism.

- *Energy:* Energy, measured in **calories**, is essential for body function. Energy consumed from carbohydrates, lipids, or proteins is converted to adenosine triphosphate (ATP) and used at the cellular level through various pathways.
- *Structure:* Bones provide the skeletal structure to which muscle, tendons, and other tissues are attached. Water is an essential element of all of these components and also provides turgor (pressure within a cell) for cells. In addition, minerals, proteins, and lipids are important for structural development.
- *Metabolism:* Metabolism refers to all the biochemical reactions throughout the body, as well as their regulation. Protein enzymes, minerals, and vitamins all mediate metabolic functions.

The U.S. government has established recommended **dietary reference intakes (DRI)** to help us meet our nutritional needs. These recommendations vary according to body mass, gender, activity level, and age (Table 5-1). Foods must

TABLE 5-1

Average dietary reference intakes to provide adequate nutritional levels for men and women ages 19–50. *Adapted from the Food and Nutrition Board (2005).*

Nutrient	Men ages 19–50	Women ages 19–50
Calories	2900	2200
Fat (grams)	28	28
Carbohydrates (grams)	130	130
Dietary fiber (grams)	38	25
Protein (grams)	56	46
Calcium (milligrams)	1000	1000
Iron (milligrams)	8	18
Sodium (grams)	1.5	1.5
Water (liters)	3.7	2.7

be labeled to reflect the nutritional contents (Figure 5-1). In addition to essential nutrients, food labels must now also contain information about the content of dietary fiber, cholesterol, fat, and trans fats. These components are not essential nutrients, but they are associated with human health.

Malnutrition and *undernutrition* are two terms used to describe poor nutritional status in humans. **Malnutrition** occurs when one or more essential nutrients are lacking, even though caloric intake is sufficient. Unfortunately, malnutrition can also result from consumption of excessive levels of nutrients. In the United States, excess consumption of carbohydrates and lipid energy has resulted in an epidemic of obesity. **Undernutrition** is described as an insufficient number of calories to maintain daily energy requirements. Globally, it is estimated that nearly 20 million deaths occur each year due to a combination of malnutrition and undernutrition.

Malnutrition

In the United States, two extreme malnutrition situations have emerged—obesity and hunger. **Obesity** is an extreme form of being overweight. About two-thirds of adults in the United States are overweight, with about one-third classified as obese or severely obese. Overweight and obesity classifications are based on **body mass index (BMI)**. BMI is an ideal average weight based on age and height. Obesity is associated with increased risk of Type 2 diabetes, high blood pressure, and cancer. Americans face several challenges when dealing with excess weight gain. These include:

- widespread availability of inexpensive food;
- the trend toward highly processed and fast foods that have a high caloric content;
- aggressive marketing of fast foods;
- reduced caloric needs because of sedentary jobs and lifestyles.

Ingredients: Whole grain rolled oats (with oat bran), sugar, dehydrated apples (treated with sulfur dioxide, sodium sulfite, and sodium bisulfite to promote color retention), salt, cinnamon, calcium carbonate (a source of calcium), natural flavors, citric acid, guar gum, niacinamide, vitamin A palmitate, reduced iron, pyridoxine hydrochloride, riboflavin, thiamin mononitarte, folic acid.

Nutrition Facts

Serving Size 1 packet (40 g)

Amount Per Serving	
Calories	160
Calories from Fat	25
	% **Daily Value***
Total Fat 3 g	**5**%
Saturated Fat 0 g	**0**%
Trans Fat 0 g	
Cholesterol 0 mg	**0**%
Sodium 85 mg	**4**%
Total Carbohydrates 28 g	**9**%
Dietary Fiber 4 g	**16**%
Sugars 11 g	
Protein 5 g	
Vitamin A 0% ▪	Vitamin C 4%
Calcium 2% ▪	Iron 6%

*Percent Daily Values are based on a 2000 calorie diet. Your daily values may be higher or lower depending on your caloric needs.

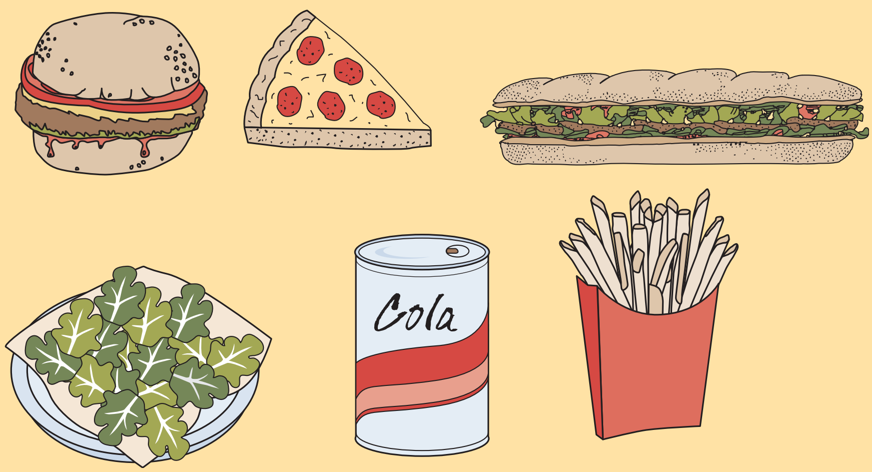
FIGURE 5-1
A sample from an oat cereal box with ingredients and nutrient content listed. All foods must list all ingredients in descending order of dry weight. In this example, whole grain-rolled oats is the first ingredient listed, followed by sugar. Labels must also supply information on nutritional facts such as energy, energy from fats, cholesterol, protein, dietary fiber, minerals, and vitamins. Fat, cholesterol, carbohydrate, fiber, protein, and selected vitamins must be presented as a percentage of daily value. Reading the food label will help you to select healthy foods for your diet.

In addition, some humans may be genetically predisposed to overeating and fat accumulation. These may have been good survival traits when early humans had inadequate levels of food and were physically active as they hunted and gathered, but they are undesirable traits today. Now, to many people, physical exercise is a lower priority than work or other more sedentary activities such as video gaming and watching TV.

In contrast to challenges with food overabundance, about 17.1 million (14.6%) U.S. households reported being food insecure during 2008. The percentage of Americans who were food insecure without hunger is 8.9 percent, and 5.7 percent were food insecure with hunger. In a food insecure household, not all members have access at all times to enough food for an active, healthy life. Of the 14.6 percent of households that reported being food insecure, about 6 percent also reported that one or more household members had reduced food intake at times during 2008 because they could not afford to buy the necessary food.

What Is a Calorie?

The term *calorie* is used to describe energy. Technically, a calorie (actually short for *kilocalorie*) is the amount of energy needed to raise the temperature of 1 gram of water 1 degree Celsius. Most adults need to consume from 2000 to 3000 calories per day. Lipids (fats and oils) are high in energy and provide 9 calories per gram, whereas each gram of carbohydrate or protein contains only about 4 calories. Lipids are energy dense. Foods high in lipids should be eaten in moderation to reduce caloric intake. These foods include fast-food hamburgers, french fries, and pizza (Figure 5-2). A key to controlling caloric intake is to gain knowledge of the calorie content of what you are eating. All packaged foods must have labeling to indicate caloric content per serving. In addition, many fast-food restaurants now show calorie and fat content of their food choices. To gain a perspective about caloric intake, study the average caloric requirements for an adult per day and compare them with how many calories are in one large, loaded hamburger, a large order of french fries, and a large, regular soda from a national fast-food restaurant chain. For many people, one meal of these types of food may represent nearly half of their daily caloric needs.

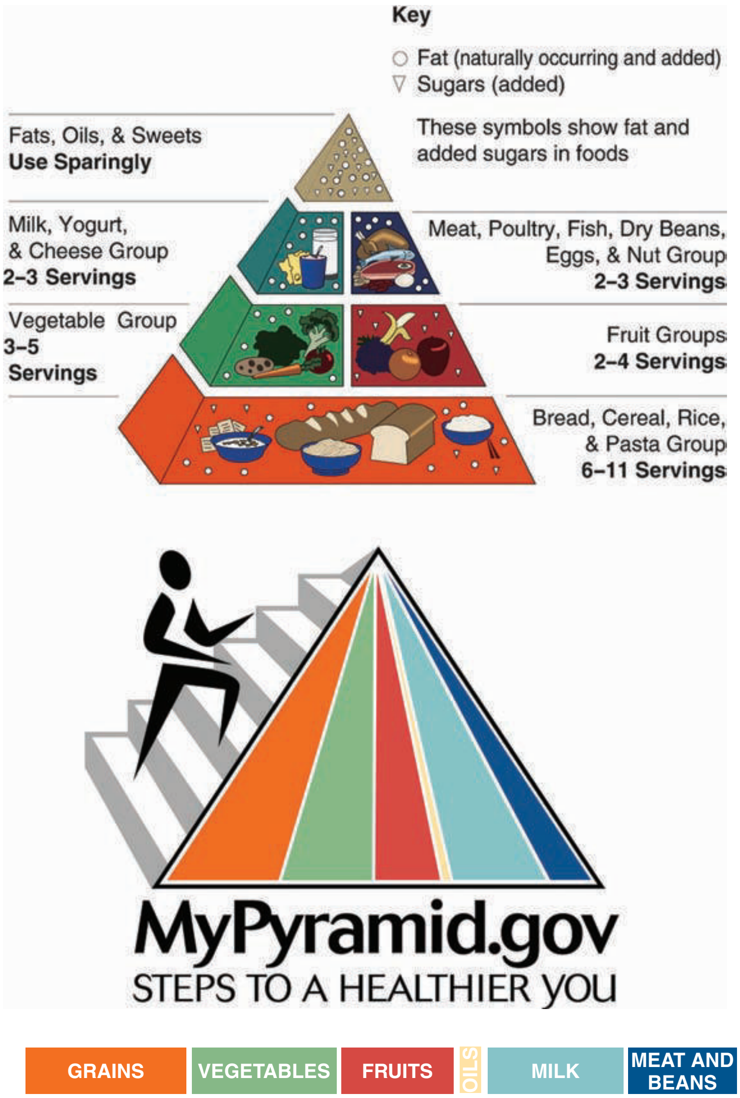


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FIGURE 5-2 Caloric and fat content of fast food and salad. A Big Mac contains 600 calories and 33 grams of fat; a slice of Pepperoni Lover's Pizza from a medium pizza contains 300 calories and 14 grams of fat; a 6-inch turkey breast sandwich contains 280 calories and 5 grams of fat; an all-vegetable salad with lettuce, mushrooms, and onions contains 56 calories and 1 gram of fat; a Coca Cola Classic (12 ounces) contains 145 calories and no fat; french fries contain 350 calories and 16 grams of fat.

The Food Guide Pyramid

To provide simplified dietary guidelines for meeting the nutritional needs of the average American, the U.S. Department of Agriculture (USDA) and the U.S. Department of Health and Human Services (HHS) developed the **Food Guide Pyramid**. The original Food Pyramid (Figure 5-3) suggests eating more servings of foods at the base of the pyramid that are high in carbohydrates such as pasta and bread; intermediate amounts of vegetables, fruits, and meats (the middle of the pyramid); and very small amounts of fats, oils, and sweets (the top of the pyramid). The 2005 version of the Food Guide Pyramid, MyPyramid, provides a triangular representation varying in area size to represent different recommendations for the daily servings of the different food groups (Figure 5-3). MyPyramid encourages the consumption of whole grain products and emphasizes the importance of physical activity for fitness and good health. The latest version of the



Adapted from the USDA and the U.S. Department of Health and Human Services (2007).

FIGURE 5-3
Food pyramids provide some simple dietary guidelines. The top pyramid was created in the 1990s and was succeeded by MyPyramid (bottom), which encourages consumers to combine healthy eating and physical activity.

Food Pyramid is described at <http://www.mypyramid.gov/>. The following are examples of what each food group includes.

- Grains that are consumed whole or processed as bread, cereal, and pasta contribute carbohydrates, vitamins, minerals, energy, and fiber and are low in cholesterol, lipids, and sugars. **Whole grains** of wheat, barley, oat, rye, millet, rice, quinoa, and amaranth in breads, cereals, and pastas are preferred. Cookies, cakes, pizza, and donuts are less desirable, because they generally contain highly processed starch and usually have added sugar.
- Fruits contribute vitamins, minerals, natural sugars, and fiber. They contain no cholesterol or fats. They are generally low in energy (calories). Fruits include apples, bananas, blueberries, grapefruit, peaches, and pears. Canned fruit, orange juice, and other fruit juices are less desirable than fresh fruit, because they often contain added sugars.
- Vegetables contribute vitamins, minerals, and fiber. They contain no cholesterol or fats, although some do contain natural oils. Vegetables include carrots, sweet potatoes, spinach, lettuce, brussels sprouts, broccoli, and cabbage; also included in this group are sweet corn, peas, potatoes, field beans, and soybeans. However, altering vegetables can compromise their nutritional value. For example, french-fried potatoes are high in fat due to processing, and potato salad and coleslaw may contain high-fat mayonnaise that is made from oil and eggs.
- Meat, poultry, fish, eggs, nuts, and dry beans (legumes) (Figure 5-4) are important sources of protein, minerals, and energy. However, this is a diverse group of nutrient sources that varies in composition. Meats from cattle, sheep, hogs, and poultry can have significant fat and cholesterol content. Eggs (especially



Keith Weller, USDA-ARS.

FIGURE 5-4
Protein sources include eggs, legumes, poultry, beef, cheese, and seafood.

the yolks) have high cholesterol content. Certain fish are a good source of essential fatty acids. Beans—including field beans, peas, and soybeans—are significant sources of protein from vegetables and do not contain fat or cholesterol.

- Milk, yogurt, and cheese are sources of protein, minerals, and vitamins such as calcium and Vitamins A and D. Whole milk products contain considerable amounts of saturated fat.
- Fats, oils, and sweets provide energy and sometimes increase the palatability of foods, but they generally provide little nutritional value. Fats are lipids from animals, whereas oils are extracted from plants. Fats are consumed along with animal meats. Also, fats and oils are often ingredients incorporated into other food products or are used in cooking methods such as frying. They are also found in confectionary products such as cookies, cakes, and donuts. The primary sweeteners used in foods are sucrose and high-fructose corn syrup (HFCS), both from plants. These sweeteners are widely used in soda, fruit drinks, candy, and desserts, and they are hidden in many other foods that are not considered sweets.



What Is a Whole Grain?

MyPyramid emphasizes the importance of eating whole grains from cereal crops such as wheat, barley, oat, and rice. Whole grain breads are more nutritious than other products made from only white, processed flours. The body digests whole grains more slowly, and they do not cause the sharp rise in blood sugar that occurs with the digestion of processed grains. Whole grain products include the entire grain kernel—endosperm, bran, and germ (Figure 5-5).

- The endosperm is the energy-storage part of the kernel and is about 84 percent of the kernel weight. It contains carbohydrates, iron, B-vitamins, and some soluble fiber. The endosperm is the portion of the kernel that is ground into white flour.
- The bran or covering of the grain is about 14 percent of the kernel weight. It contains B-vitamins, minerals, and insoluble dietary fiber.
- The germ is the embryo or immature plant and contains only about 2 percent of the kernel weight. It is rich in vitamins, trace minerals, protein, and oil.

In flour making, the grain is first milled. During milling of wheat, the bran and germ are separated from the endosperm. The endosperm is used for producing white flour. Producing white flour is called **refining** because the white endosperm is purified of darker color specks from the bran and endosperm. Today, many flour products are **enriched** through the addition of nutrients that were lost during processing.

Dating back to Roman times, bread made of refined white flour was indicative of a higher class status, because it was more costly to produce this flour with the bran and germ removed. Whole grain products were cheaper to make and peasants consumed them. In the 1800s, an American, Sylvester Graham, promoted the consumption of whole grain breads and crackers. Most graham crackers, a food product that bears his name, are made of whole wheat and are nutritionally superior to white crackers.

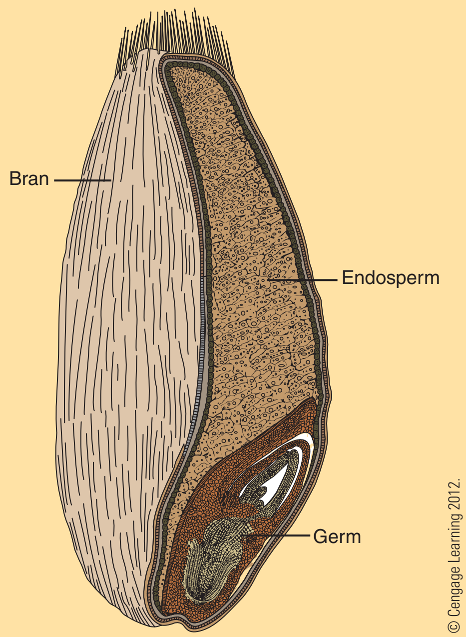


FIGURE 5-5 A whole wheat kernel consists of the immature plant embryo (the germ), starch storage (the endosperm), and an outer coating (the bran).

America's Dinner Table

American cuisine truly reflects that America is a melting pot of nations. Food-consumption patterns have changed over time based on various ethnic influences in the country, and Americans now consume a wide variety of foods. For example, cuisines have been adapted from Europe, Asia, Latin America, Mexico, and the Mediterranean region. With changes in demographics, it is difficult to describe a typical American breakfast, lunch, or dinner. However, in total we do know that the average American diet contains greater quantities of meat, flour, and fats than any other culture. Average annual food consumption is shown in Table 5-2.

Changes in Food Consumption

American food-consumption patterns have changed dramatically during the last 30 years (Table 5-3). Among the more notable changes are the decreased consumption of red meat (beef, pork, veal, and lamb), eggs, and milk. These decreases may be related to health concerns about cholesterol and saturated fats, but the consumption of cheese, a product derived from milk, has increased dramatically, likely due to its extensive use in pizza and other foods. People are eating more poultry, fats, grains, and sweeteners. Some of these food-consumption trends are associated with a significant increase in caloric consumption. Americans consume 600 calories more per day than they did in 1970.

TABLE 5-2

Average yearly personal consumption of fats and oils, milk, potatoes, cheese, flour and cereal products, eggs, fresh vegetables, poultry, legumes, fresh fruits, and red meat in the United States in 2008. *Adapted from USDA-ERS (2010).*

	Amount consumed	
Food group	**Pounds**	**Kilograms**
Fats and oils	87	39
Milk	204	93
Potatoes	67	30
Cheeses	32	15
Flour and cereal products	197	89
Eggs	244	111
Fresh vegetables	173	78
Poultry	94	43
Fresh fruits	120	54
Red meat	114	52
Sugars and sweeteners	136	62
Fish and shellfish	16	7
Legumes	7	3

TABLE 5-3

Changes in food consumption between 1975 and 2005. *Adapted from USDA-ERS (2010).*

	Change in consumption	
Food group	**Pounds**	**Kilograms**
Fats and oils	31.3	14.2
Milks	−71.0	−32.2
Rice	13.9	6.3
Cheeses	17.0	7.7
Flour and cereal products	53.6	24.3
Eggs	−48.5	−22
Fresh vegetables	61.3	27.8
Poultry	40.6	18.4
Fresh fruits	29.1	13.2
Red meat	−15.9	−7.2
Sugars and sweeteners	27.8	12.6



FIGURE 5-6
Grains from crops such as wheat, corn, and oat are made into breads, pasta, and cereals.

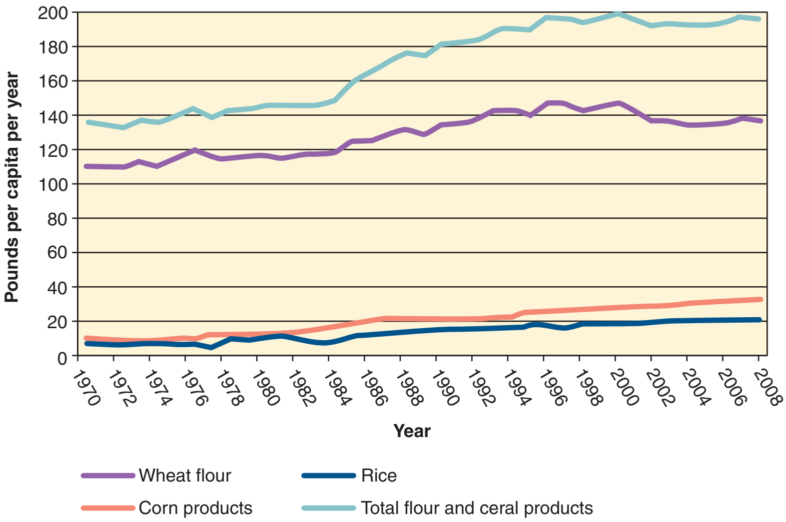


FIGURE 5-7
Per capita consumption of total flour and cereal products, wheat flour, corn products, and rice excluding quantities used in alcoholic beverages, fuel, and corn sweeteners. 1 pound = 0.45 kilogram.

Grains from Grasses

Grains from crops such as wheat, corn, and oat are processed and made into breads, pastry, pasta, and cereals (Figure 5-6), but rice is typically consumed as a whole grain with germ and bran removed. Per capita, the consumption of wheat, rice, and corn has increased dramatically since 1970 (Figure 5-7). Americans consume about 200 pounds (91 kilograms) of flour and cereal products annually per capita, a 40 percent increase since 1970. Although some whole grain bread products are continuing to be developed for the healthy foods market, much of the grain sold in the United States is currently being marketed after refining. Ninety percent of the total wheat consumed by people in the United States is white or whole wheat flour made from hard red wheat and white wheat. The remainder is durum wheat flour used for making noodles, spaghetti, and pizza dough. The consumption of durum wheat flour has increased 80 percent since 1970.

Corn product consumption per capita (excluding its use in sweeteners) has risen to about 35 pounds (16 kilograms) per year. The increased consumption is largely due to greater processing of corn to meal and flour for snack foods and tortilla products. Milled rice consumption has also increased, in part because of increased Asian immigration to the United States. Only about 5 pounds (2.3 kilograms) in total of oat, rye, and barley are consumed annually per capita with little change in the past 30 years. This is likely related to the small number of marketed products containing oat, rye, and barley.

Lipids: Fats and Oils

The average American consumes more than 80 pounds (37 kilograms) per year of added fats and oils (Figure 5-8). Fats and oils improve the taste and increase the palatability of foods, and are used in baking and cooking. Fats and oils are types of lipids. Fats such as lard from hogs and tallow from beef are saturated lipids and are solid at room temperature. Oils are extracted from plant seeds and are liquid at room temperature. Corn oil, soy oil, and canola oil are derived from plants. Consumers sometimes knowingly consume fat that is visible in meat or apply butter and solidified oil as margarine to bread; however, most lipids are hidden as ingredients of products. They are used extensively in the commercial preparation of baked goods, french fries, potato chips, and other snack foods. People consume oils as salad dressings, mayonnaise, and cooking oils, and oils are hydrogenated for use in deep frying and margarine. Volatile fatty acids are lipids that provide a tantalizing aroma when inhaled and are often used at fast-food establishments.

The consumption of butter (made from cow's milk) and lard is low because of concerns about saturated fat and cholesterol consumption. Butter use has remained stable at about 4.5 pounds (2 kilograms) per capita. Lard, a by-product from the processing of pigs, was at one time used extensively for baking, but consumption is now only about 1 pound (0.5 kilogram) per capita. During the Great Depression in the 1930s, when the availability of all foods was limited, lard was sometimes consumed directly in sandwiches as a food.

Cream is fat separated from cow's milk. Like all animal fats, it is saturated and contains cholesterol. Separated creams are sold as drink additives, cooking ingredients, and condiments. Consumption of all types of cream has increased

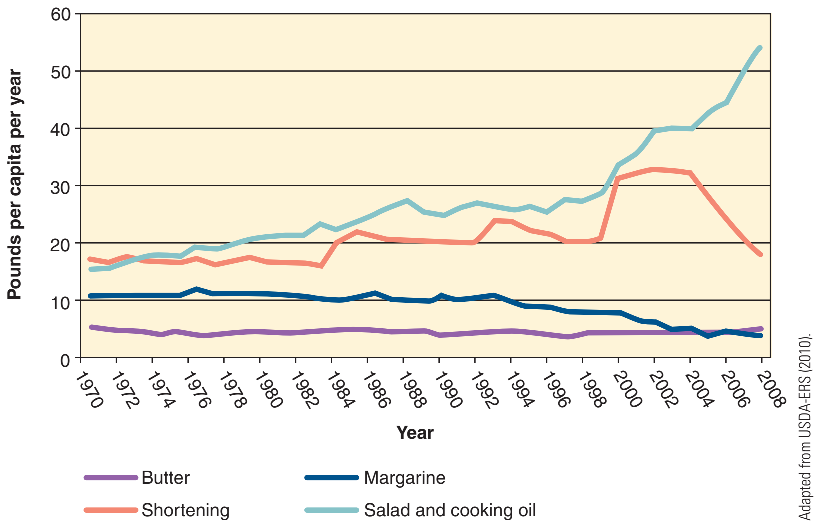


FIGURE 5-8
U.S. per capita consumption of added lipids. Fats and butter are saturated lipids produced from animals. Margarine, salad and cooking oils, and shortening are produced from plant oils. 1 pound = 0.45 kilogram.

significantly since 1970. The greatest increases have occurred with heavy cream and sour cream. Meanwhile, milk consumption has decreased since 1970 and is now about 21 gallons (80 liters) per capita. Milk is sold with variable levels of fat. Whole milk contains 4 percent fat, and skim milk contains no fat.

Sweeteners from Plants

Humans have an innate preference for sweets. Though some foods such as fruits are naturally sweet, it has become common for sweeteners to be added to processed foods and drinks. Total added sweetener consumption has increased about 25 percent since the early 1970s with current per capita consumption at roughly 140 pounds (64 kilograms) per year (Figure 5-9). In addition to being an ingredient in foods such as candy, soda, cakes, and cookies (Figure 5-10), sweeteners are now also in other

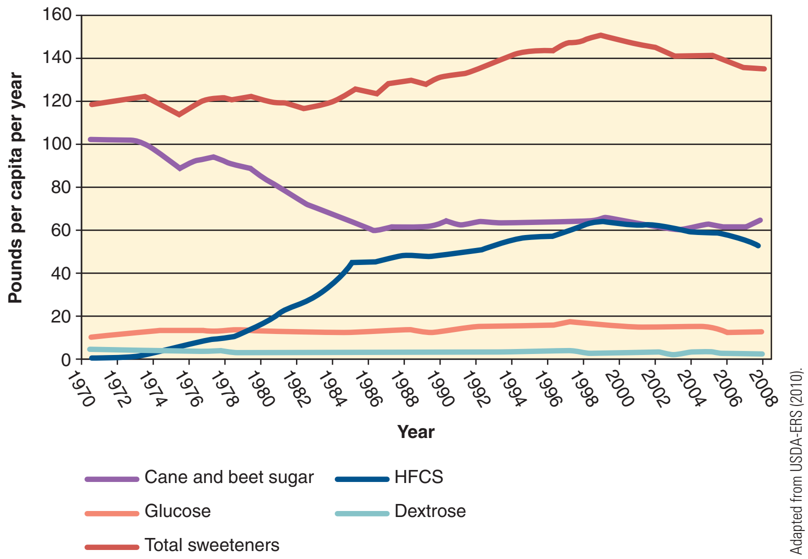


FIGURE 5-9
Per capita added sweetener consumption. HFCS, cane sugar, and beet sugar are the primary sweeteners. 1 pound = 0.45 kilogram.



FIGURE 5-10
Cakes, cookies, pastries, and pies are some of the sweet foods that we consume.

processed foods such as soups and salad dressings. Because of its low cost and high level of sweetness (it is about two times sweeter than sucrose), HFCS is the primary sweetener used in most regular sodas, artificial fruit drinks, and most candy products. Today, Americans consume more than 46 gallons (174 liters) per capita of soft drinks compared with about 21 gallons (80 liters) per capita of milk. Sugarcane and sugar beets contain sucrose (sugar) that is refined to produce table sugar.

Meats

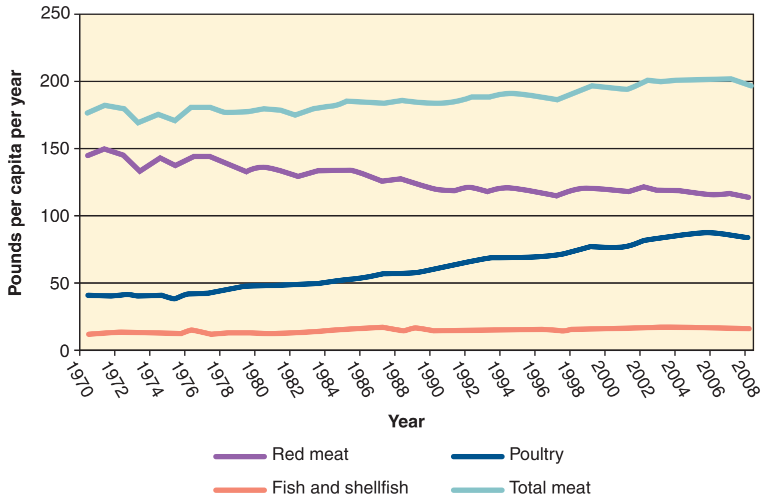
The average American diet has always been rich in meat, but the total annual consumption is now about 200 pounds (90 kilograms) per capita, an increase of 15 percent since 1975 (Figure 5-11). Although consumption of red meat (beef, pork, veal, and lamb) has decreased 10 percent since 1970, red meat still comprises nearly 60 percent of the total meat consumed. Like red meat, egg consumption has also decreased. In contrast to red meat and eggs, poultry consumption has increased 90 percent since 1970. Meats contain high levels of protein with balanced amino acid profiles; however, most red meats are high in saturated fats and cholesterol. Red meat contributed 20 percent of the total saturated fats in the average American diet in 2000, and poultry contributed 6 percent. Meat production is directly related to crops, because during the final feeding of livestock before slaughter, a diet high in grain including corn and soybeans is commonly fed (Table 5-4 and Figure 5-12). However, some farmers are producing grass-fed meats that are lower in fats.

Stevia

Stevia (*Stevia rebaudiana*), a member of the sunflower family (Asteraceae), is an herb native to South America. It has been used as a sweetener for thousands of years by native South Americans and has more recently begun to be utilized as a sugar substitute especially suited to those on reduced-calorie diets. The plant leaves contain sweet glycosides that contain steviol ($C_{20}H_{30}O_3$), which can be 30 to 300 times sweeter than sugar. Compounds refined from stevia are marketed in the United States under the trade name Truvia, by Cargill and the Coca-Cola Corporation, and also as Purevia, by PepsiCo and Pure Circle.

Similar to other sugar substitutes, there is much controversy surrounding the use and safety of stevia. Some research has found that stevia may have mutagenic or toxic effects, but most studies have shown no ill effects. In 2006, the World Health Organization, after reviewing relevant research, concluded that stevia was not a toxic substance to embryos, humans, or animals.

Stevia is widely used as a sweetener in Japan and as a food additive or dietary supplement in Australia, the United States, Brazil, Mexico, and other countries, but is banned in several regions including the European Union. The United States FDA had labeled stevia as an unsuitable food additive owing to the unresolved nature of the research surrounding its toxicity, but has relaxed its restrictions and approved Truvia and Purevia.



Adapted from USDA-ERS (2010).

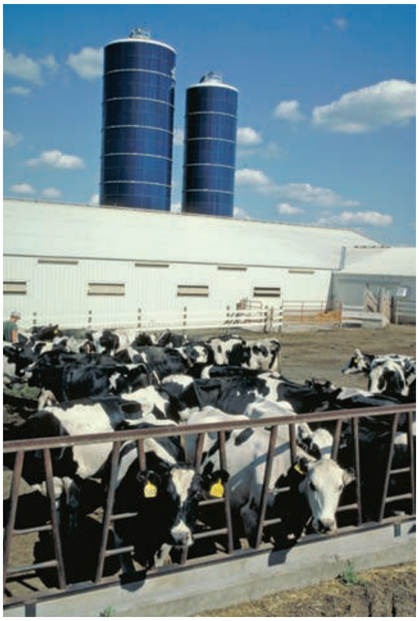
FIGURE 5-11
Per capita consumption of red meat (beef, pork, lamb, and veal), poultry (chicken and turkey), and fish and shellfish. 1 pound = 0.45 kilogram.

TABLE 5-4

Typical crops and example percentages of each crop in the diets of livestock raised for milk and meat production. *Adapted from Board on Agriculture (1994, 2000, 2001).*

Dairy cow		Beef steer		Chicken broiler (all ages)	
Alfalfa	25%	Corn silage	75%	Corn	60%
Corn silage	40%	Corn grain	20%	Soybean meal	23%
Corn grain	25%	Soybean meal	5%	Canola	5%
Soybean meal	10%			Blood meal	2%





David L. Hansen, University of Minnesota.

FIGURE 5-12
Beef and dairy cattle are fed grains or herbage from plants. Corn and soybean are important ingredients in the rations of these animals.



FIGURE 5-13
Feeding chickens in the 1930s.

The consumption of chicken in the United States has increased by almost 600 percent in the past 100 years. This great increase is a good example of how changes in technology and food processing affect consumer demand.

- In the early 1900s, most chickens were still raised as "free range" with the majority of chickens kept in smaller farm flocks (Figure 5-13). Chickens obtained food from foraging for insects, spiders, and succulent plant material such as clovers. Some grain feeding occurred, but it was limited. The typical chicken meat came from older hens and young roosters that were not useful to the egg-laying industry. Meat availability was also very seasonal with most meat being available during the summer and early fall.
- During World War II, the U.S. government controlled distribution of most meats except poultry. Farmers began raising chickens solely for meat production. However, the seasonal availability was still limited. Purchase and home-processing of whole chickens was commonplace. For example, in the 1940s, *Good Housekeeping Cookbook* provided instructions to homemakers for plucking and drawing (removing entrails, head, and feet) of the chicken.
- Following World War II, development of improved chicken breeds (e.g., Cornish-white rock crosses), synthetic vitamins, formulated rations, and confinement feeding increased meat availability and lowered prices by 30–40 percent compared to the 1920s. Poultry feed made of concentrated energy rations containing corn and other grains became common. The supermarket concept was developed to facilitate the mass marketing of chicken.
- In the 1950s, in response to consumer demand for increased convenience, TV dinners were introduced. They often contained fried chicken or turkey. The first Kentucky Fried Chicken franchise opened in 1952.
- In the 1970s, a large number of processed, easy-to-cook products were developed, and sales of whole chickens fell from 70 percent to about 20 percent.
- In 1983, McDonald's introduced the Chicken McNugget, a fast food very popular with children. The McNugget is a deep-fried product made from ground chicken meat.
- In the 2000s, in response to public concern about healthy meat, chicken meat and eggs began to be marketed as free range and retailed at a premium price





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FIGURE 5-14
Turkeys raised in confinement (left) and free range (right). Today, there is a renewed interest in free-range poultry. In contrast to confined systems, this poultry gets some nutrients from herbage, insects, and weed seeds.

(Figure 5-14). Free-range chickens are raised on pasture and derive a portion of their daily rations from insects; however, in contrast to earlier times, most of these free-range chickens receive some grains in their diets to increase their rate of gain.

Vegetables and Fruits

Improvements in processing and distribution systems have facilitated enhanced year-round availability of many fruits and vegetables. Total vegetable consumption has increased nearly 25 percent in the past 30 years, in part because of the recognition of health concerns associated with consumption of meats and meat products. Of vegetables consumed, about 55 percent are processed (mostly canned or frozen) and 45 percent are fresh. The largest vegetable group consumed is potatoes (eaten as french fries, potato chips, instant, and baked) followed by tomatoes (canned and fresh), corn (canned and fresh), lettuce (iceberg, romaine, and leaf lettuce), carrots, and onions.

Fruit consumption has also increased by 5 percent in the past 30 years. We eat about 55 percent of fruit as processed fruits and the remaining 45 percent as fresh. The largest fruit groups consumed are fresh citrus (oranges and grapefruit), melons (watermelon and cantaloupe), juices (orange juice and apple juice), bananas, and fresh apples.

Factors Affecting What We Eat

Culture, lifestyle, food availability, and food cost combine to influence our eating patterns. In the United States, food availability and cost are directly affected by our crop production practices.

Food Availability

The United States has benefited from its diverse environments and resources to produce a variety of foods. Specific climates and soil conditions enable some regions to be ideally suited for the production of specific crops. In addition, the globalization of agriculture has allowed for the routine international flow of food products between countries. The development of efficient transportation, distribution, and processing systems has made a variety of foods available on a year-round basis. Grocery stores can stock their shelves with a tremendous selection of food products.

Food Cost

Over the past few decades, Americans have been spending a declining percentage of their monetary budgets on food. This is related to not only the increase in per capita income, but also to a decrease in food prices. Americans pay less for food than people in any other country in the world (Table 5-5). This is due to the abundance of resources in this country and to the industrialization of the agricultural production and processing systems. Federal and state governments provide direct subsidies (payments) to farmers to maintain the production of commodities. Many agricultural inputs are also subsidized; for example, in the western United States, water is provided to many dry regions through a government-financed system of dams and canals.

TABLE 5-5

Percentage of per capita income spent on food, by nation. *Adapted from USDA-ERS (2007b).*

Country	% of income spent on food
United States	10.9
United Kingdom	11.5
Sweden	14.5
Australia	14.6
France	15.2
New Zealand	15.7
Italy	17.6
Germany	17.7
Japan	17.8
Israel	21.0
Spain	21.0
South Africa	27.0
Mexico	33.2
India	51.4

Fuel used for tractors, food transportation, and fertilizer manufacturing is also cheaper in the United States than most countries of the Western world. With increasing energy and commodity costs, it is likely that food costs will also increase in the United States. Some policy makers and citizens are concerned that commodities such as corn, soybean, and wheat are used extensively for production of processed foods and are supported by subsidies, whereas fruits and vegetables, which are deficient in many diets, are not supported. American agriculture is very fossil-fuel dependent. For example, growing 1 kilocalorie of food and bringing it to the dining table uses about 10 kilocalories of fossil fuel. Energy is consumed not only to grow and transport food, but also for food-related tasks such as fertilizer production and food processing.

Energy from Plants

Bioenergy crops are a renewable energy source. They use carbon energy captured through photosynthesis and, in contrast to fossil fuels, their combustion does not result in a net increase in the atmospheric carbon dioxide concentration. Worldwide, only about 15 percent of the energy used by humans comes from bioenergy crops. Most of this energy is used through direct combustion (burning) of forest products and crop residues.

About 84 percent of all the energy consumed in the United States is from nonrenewable fossil-fuel resources (Table 5-6). Only 7 percent is from renewable sources such as plant biomass, hydroelectricity, wind, and the sun. Biomass and hydroelectricity contribute the majority of the renewable energy used in the United States. Most of the biomass used for energy in the United States is provided by the forest-products industry, urban tree trimming, and fuel wood. Also, a small quantity of switchgrass is being cofired with coal in combustion facilities.

TABLE 5-6

Sources of energy consumption in the United States, 2008. *United States Energy Information Administration, 2010.*

Energy source	Percentage of total energy
Natural gas	24.0
Petroleum	37.4
Coal	22.6
Nuclear	8.5
Biomass	3.9
Hydroelectric	2.5
Wind	0.5
Geothermal	0.4
Solar	0.1

Energy Policy

Historically, we have taken for granted the availability of low-cost energy in the United States. Taxpayers have subsidized the fossil fuel energy industry. In the 2000s, public awareness about energy issues grew because of several developments:

- High prices for gasoline at the pump have caused a significant change in consumer spending.
- Dependence on imported foreign oil from Venezuela and the Middle East have caused national security and balance of payment concerns.
- Excessive greenhouse-gas production from burning fossil fuels such as petroleum and coal has been associated with climate change.

The Energy Independence and Security Act of 2007 was passed by the U.S. Congress and signed by the president to create greater energy independence and security, and to increase the production of clean, renewable fuels while minimizing greenhouse-gas production. The act established a renewable fuel-use standard of 36 billion gallons of bio-based transportation fuels per year by 2022. Of this, 15 billion gallons will come from the established corn ethanol industry, while the remainder will come from advanced biofuels. These include cellulosic ethanol (16 billion gallons), biodiesel (1 billion gallons), and other fuels like methanol and biobutanol (4 billion gallons). To provide for this demand, several different crops will supply feedstock for conversion to energy (Table 5-7). According to the USDA (2010), in the southeast United States, feedstock will be supplied from soybean, biomass sorghum, perennial grasses, and woody biomass; in the northeast, energy feedstocks will be supplied by woody biomass; in the central region, feedstock will be supplied from corn grain, perennial grasses, corn stover, small grain straw, and soybean; in the northwest region, feedstock will be supplied by woody biomass, canola, grass, and small grain straw; and in the west, feedstock will be supplied from woody biomass, canola, and camelina.

The development of biofuels from agricultural crops provides for expanded and new markets for agricultural crops and enhanced rural development. In addition, the development of the renewable-fuels industries provides significant new

TABLE 5-7

USDA-estimated billion gallons of fuel by feedstock in 2022. *Adapted from the USDA (2010).*

Feedstock	Billion gallons
Dedicated energy crops: switchgrass, miscanthus, sugar cane, sorghum	13.4
Oilseeds: soybean, canola, camelina	0.5
Crop residues: corn stover, small grain straw	4.3
Woody biomass: logging residues	2.8
Corn starch ethanol	15.0

economic opportunities. For the existing corn ethanol industry, a study by Urbanchuk (2009) at the Renewable Fuels Association indicates the following:

- The ethanol industry added $53.3 billion to the nation's gross domestic product (GDP) in 2009. This included spending for infrastructure and operation of all plants.
- The ethanol industry is a significant employer of workers in construction, transportation, and in research. Many jobs are at new facilities in rural areas. In total, the ethanol industry supported nearly 400,000 jobs in all sectors of the economy.
- The ethanol industry generated an estimated $8.4 billion in tax revenue for the federal government and nearly $7.5 billion of additional tax revenue for state and local governments.

An important criterion for selection of crops for biofuel production is their level of greenhouse gas (GHG) production (see Chapter 10). According to the USDA (Wang et al., 2007), ethanol produced from corn results in about a 20 percent reduction in GHG emissions relative to gasoline. Cellulosic biomass produced from perennial grasses would potentially result in nearly a 90 percent reduction in GHG emissions relative to gasoline because of the reduction in inputs of energy and synthesized fertilizers and pesticides.

Corn Ethanol

In the United States, corn is the leading crop used for ethanol production. Corn's starch is easily extracted and is a uniform substrate for ethanol production. In 2007, almost 5 billion gallons (19 billion liters) of ethanol were produced from corn. About 2.8 gallons (11 liters) of ethanol are produced per bushel (25.4 kilograms) of corn. Therefore, an acre (0.4 hectare) of corn with a yield of 150 bushels (3800 kilograms) of corn grain produces 420 gallons (1600 liters) of ethanol.

The number of ethanol-producing refineries and their production capacity has increased dramatically (Figure 5-15). To minimize transportation costs, most

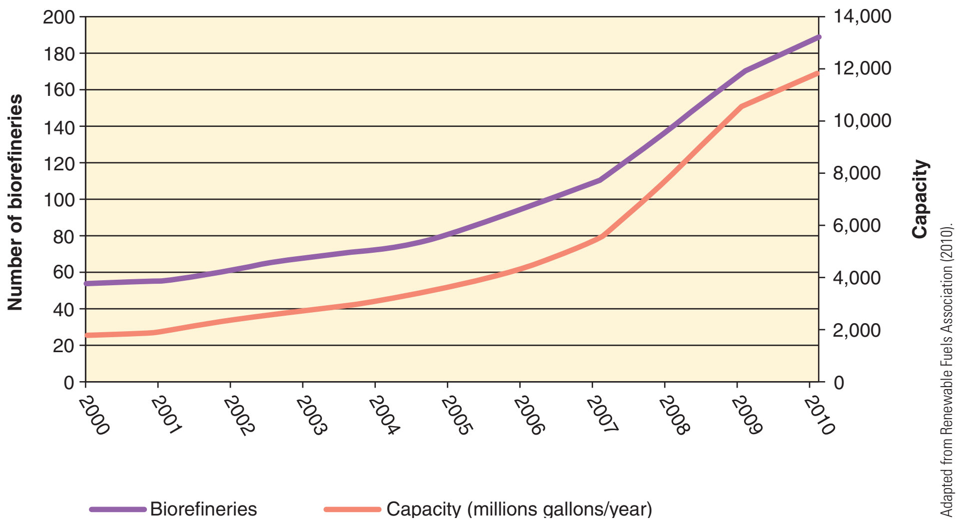


FIGURE 5-15 Number of biorefineries and ethanol production capacity in million gallons per year (mgy).

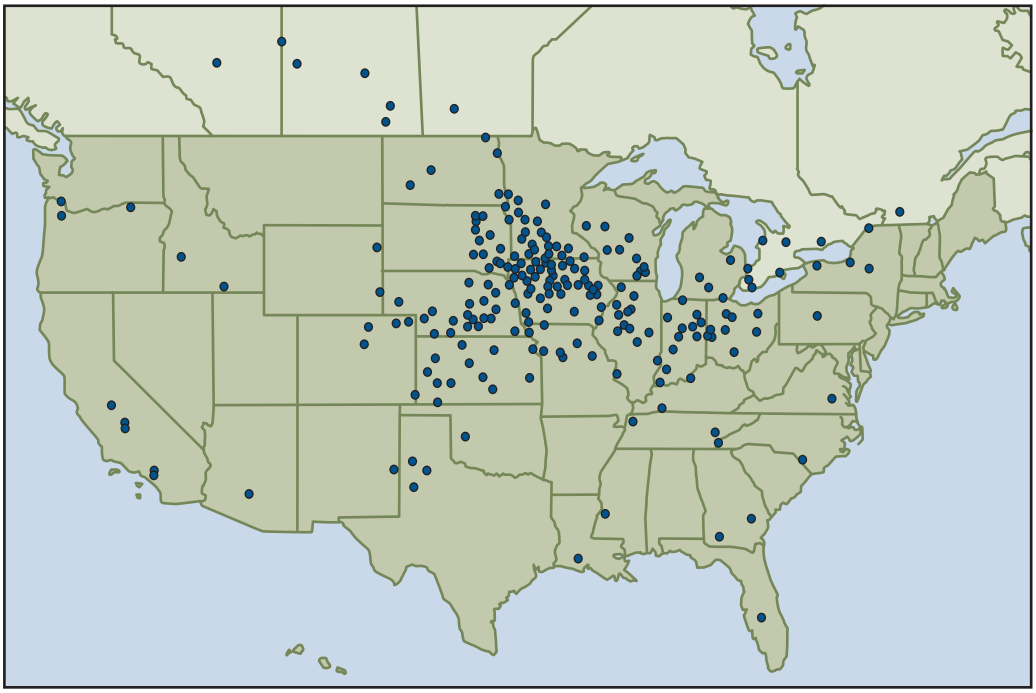

Adapted from Ethanol Producers Magazine (2010).

FIGURE 5-16 Ethanol refineries in the United States and Canada.

of these refineries are located in the Midwest near areas of corn production, but other refineries are also dispersed throughout the United States and Canada (Figure 5-16). A few use alternative sources of energy for fermentation. Refineries in Kansas and North Dakota sometimes use starch from wheat, barley, and sorghum. A plant in Idaho uses the starch from potato waste. A plant in Louisiana uses sugar from sugarcane.

Ethanol is typically blended with gasoline for use as a transportation fuel. Most blends are limited to 10 percent ethanol because of concerns about ethanol's effect on engine components. However, ethanol proponents are advocating for greater use of ethanol and blends containing 15 percent ethanol. Flexible-fuel vehicles have engines that can use blends containing up to 85 percent ethanol (E85) as well as pure gasoline. Ethanol contains about two-thirds the energy as that of gasoline; therefore, mileage obtained per gallon may be less. There are about 76,000 Btu of energy in a gallon of ethanol and 116,000 Btu of energy in a gallon of gasoline.

Corn ethanol can be produced by a wet milling or dry milling. In wet milling, the whole corn grain is soaked in water and then separated into germ, endosperm, and seed coat parts. In contrast, in dry milling the whole kernel is ground. Most corn-ethanol production is by the dry milling process:

1. Milling or grinding the grain into a fine powder or corn meal
2. Liquefying the corn meal with water and heat
3. Using enzymes to convert the starch to glucose
4. Using yeast to ferment the glucose to produce ethyl alcohol $C_6H_{12}O_6 \longrightarrow C_2H_5OH + 2\ CO_2$
5. Separating and concentrating the ethanol from water and other impurities by using distillation and other separation technologies



Steven Vaughn, USDA-ARS.

FIGURE 5-17 Distillers dried grains held in storage at an ethanol plant in Iowa.

TABLE 5-8

Average composition of corn grain and distillers grains on a dry-matter basis. *Adapted from Weiss et al (2007).*

	Corn grain	Distillers grains
Crude protein	9.4	30.0
Neutral detergent fiber	9.5	40.0
Starch	70.0	4.0
Crude fat	4.2	12.0
Phosphorus	0.3	0.8

One of the important by-products of ethanol production from corn grain is **distillers grains** (Figure 5-17). About 17 pounds (8 kilograms) of distillers grains are produced after the ethanol is separated from the processed grain. Wet distillers grains usually have about two-thirds water and contain protein, fiber, fat, and minerals (see Table 5-8). Distillers grains are a valuable source of livestock feed and can be either directly fed or dried.

Corn-Ethanol Challenges

Increased production of ethanol from corn to achieve a goal of 15 billion gallons (57 billion liters) will require use of a significant amount of the corn produced in the United States. In the future, there may be competition for corn normally used for livestock and human food resulting in increased prices for meat, eggs, and corn products. This challenge can be overcome with increases in production by farmers brought about by new corn genetics and improved management practices.

Some people are concerned about the energy and water use efficiency of producing ethanol from corn. Energy is used in many phases of corn production and in processing. However, in the overall energy balance, corn ethanol is

positive because in terms of energy use, each gallon of ethanol produced from corn provides one-third or more energy than is used to produce it (National Renewable Energy Laboratory, 2010). It currently requires about 3 gallons (11 liters) of water per gallon of ethanol produced; and water can be a limiting factor in some environments. However, with refinements in technology it is projected that a one-to-one ratio of water used to ethanol produced can be achieved. In evaluating the energy and water concerns of corn ethanol production, it is important to remember that gasoline production also requires significant inputs of energy and water during production. For example, it requires nearly 2.5 gallons (9 liters) of water for each gallon of gasoline produced (Renewable Fuels Association, 2010).

Corn ethanol production is subsidized in several ways. First, eligible growers can receive commodity support payments. In addition, there are federal and sometimes state support in the form of tax credits for producing and blending ethanol. This support is considered by many to be necessary for the ethanol industry to develop in the face of subsidized competition from the petroleum industry.

Cellulosic Ethanol

Production of ethanol from cellulose is attractive because of the abundance of cellulose produced by plants in the United States. Perlack et al. (2005) estimated that more than a billion dry tons (91 million metric tons) per year of low-cost fuels could be produced. Potential cellulosic ethanol sources fall into the categories as described in Table 5-7. These include crop residues, forest residues, and dedicated energy crops. In addition, surplus or damaged hay crops of alfalfa or smooth bromegrass could be processed into biofuels. One advantage of cellulosic ethanol as compared to corn grain ethanol is that perennial crops can be used, which have a lower impact on the environment.

The cellulose content of crop residue and dedicated energy crops averages about 40 percent, although the concentration of cellulose can be affected by crop, management, and environment. These crops also contain a significant amount of hemicellulose (~30%) and lignin (~15%). The complex nature of the carbohydrates found in corn and switchgrass are shown in Table 5-9.

Cellulosic crops yield 60–80 gallons (227–303 liters) of ethanol per ton (0.91 metric ton) of crop biomass. Unfortunately, currently there is no commercial production of ethanol from cellulosic feedstock in the United States. Technology is in development to greatly increase the efficiency of the conversion process. Though the starch in corn grain can be readily converted to glucose and then fermented to ethanol, the cellulose in plants is not easily converted. Cellulose is less available because it is bound to lignin and hemicellulose. Also, the cellulose structure is more difficult to degrade by enzymes than is starch. Cellulose chemistry is explained in more detail in Chapter 6.

The current process of ethanol production from cellulosic plant material has the following steps:

1. Grinding the plant material
2. Treating with acid, pressure, and heat to break linkages between lignin, cellulose, and hemicellulose. This step also degrades hemicellulose into a mixture of simple five-carbon and six-carbon sugars (xylose).
3. Using cellulase to convert the liberated cellulose to glucose

TABLE 5-9

Composition (in percent dry matter) of cellulosic biomass. *Adapted from Jung (2010).*

Cell wall component	Corn Stover	Corn Cob	Switchgrass herbage
	% DM		
Glucose	29	29	26
Hexose	31	30	28
Xylose	19	26	19
Pentose	22	29	22
Total sugars	55	62	52
Lignin	9	9	17

4. Glucose from cellulose is fermented by yeast to produce ethanol, and xylose from hemicellulose is fermented by bacteria to produce ethanol.
5. Distilling and concentrating the ethanol

Cellulosic Ethanol Challenges

In contrast to corn, there are several challenges facing cellulosic ethanol. These include: the difficulties with efficient processing of the complex carbohydrates in herbaceous and woody plant materials, variation in the chemical composition among plant materials, and challenges in transporting, storage, and handling of the bulky plant material. The Biomass Crop Assistance Program in the Food, Conservation, and Energy Act of 2008 (Farm Act) was developed to provide incentives and lower feedstock costs for production of cellulosic biofuels. This program provides financial assistance for collection, harvest, storage, and transportation costs associated with materials such as crop resources (corn stover and cobs), herbaceous resources (switchgrass), and forestry residues. The overall cost effectiveness of cellulosic ethanol production will likely initially be low.

To meet the renewable fuel standard goals in the Energy Independence and Security ACT, the Biomass Program in the U.S. Department of Energy (see http://www.eere.energy.gov/ for more information) has initiated and funded programs with industry and universities throughout the United States to address these challenges. One program involves the demonstration of integrated biorefineries as strategies to increase the conversion efficiency and cost effectiveness of using cellulosic feedstocks. Integrated biorefineries utilize both biochemical and thermochemical conversion processes to convert cellulosic materials to both high-value products such as plastics and adhesives, as well as low-value products like ethanol in large volume. In addition to ethanol, biorefineries would have potential to produce fuels such as bio-oils that could be subsequently converted to other fuel. Biorefineries would recycle heat generated in conversion processes and would be energy self-sufficient.

Biodiesel

Biodiesel is a renewable substitute for petroleum-based diesel. It is produced from soybean, canola, and camelina. Oil extracted from these crops is reacted with alcohol in the presence of a catalyst. The chemical process is called transesterification and produces methyl esters of fatty acids (biodiesel) and glycerin (a by-product). About 1.5 gallons (5.7 liters) of biodiesel and 48 pounds (22 kilograms) of soybean meal are produced from a bushel of soybean. About 100 billion gallons (379 billion liters) of biodiesel are produced annually in the United States. It is often used as a blend with petroleum diesel.

Energy Research

The National Renewable Energy Laboratory (NREL) in Golden, Colorado, is the primary laboratory for renewable energy research and development in the United States. NREL is a laboratory of the U.S. Department of Energy (DOE). NREL's mission statement is: "NREL develops renewable energy and energy efficiency technologies and practices, advances related science and engineering, and transfers knowledge and innovations to address the nation's energy and environmental goals." NREL conducts research and development in renewable electricity and fuels, energy system engineering, and energy analysis. In the area of biomass research, NREL is studying approaches to convert biomass from grasses, corn stover, wood waste, and algae to fuels. See their website http://www.nrel.gov/.

One of the approaches scientists at NREL and other agencies use to study the environmental and energy impact of alternative fuels is Life Cycle Assessment (LCA). The analysis considers the energy inputs and outputs at all stages leading to ethanol production. The major inputs and outputs of an energy life-cycle analysis for ethanol produced from corn grain are shown in Figure 5-18. Ultimately,

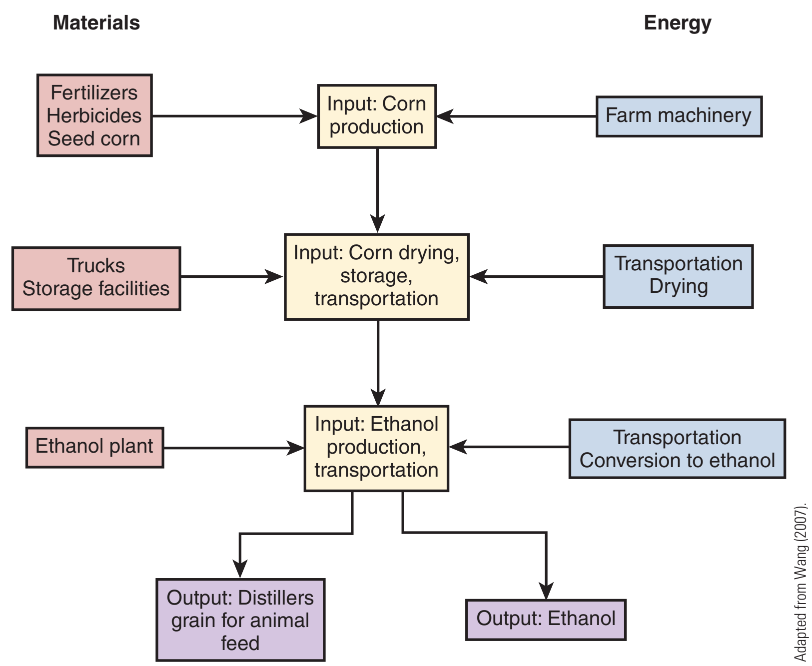


FIGURE 5-18
Energy inputs and outputs for corn grain ethanol production used to develop a Life Cycle Analysis. For every Btu of ethanol produced, it requires 0.78 Btu of fossil fuels.

TABLE 5-10

The amount of energy inputs needed in the production of various energy sources to drive one mile. This considers the energy to produce the fuel as well as the fuel efficiency. The switchgrass and corn stover figures are theoretical. In this example, corn stover requires the least energy inputs. 1 Btu = 1055 joules. 1 mile = 1.6 kilometers. *Adapted from Sheehan, NREL (2002)*.

Energy source	Btu to drive one mile
Gasoline	5755
Ethanol from corn grain	3361
Ethanol from switchgrass	1704
Ethanol from corn stover	825

the analysis can show the relative energy use of alternative energy sources (Table 5-10). Life-cycle analysis can also study the greenhouse-gas emissions and total environmental impact of alternative energy production systems.

Review Questions

1. What are the essential categories of nutrients for humans, and what are they used for in our bodies?
2. Identify a crop used as a human food source and list the specific nutrients it would supply.
3. Describe dietary reference intakes and the food labels that go along with them.
4. Discuss the difference between malnutrition and undernutrition.
5. How prevalent is obesity and being overweight in the United States? What health problems are associated with the high number of people who are obese and overweight? What are some of the physical conditions that result from being overweight and obese?
6. What is a calorie, and about how many calories does the average person need to consume in a day?
7. What food groups are defined by MyPyramid? What does it suggest in regard to eating habits?
8. What types of food does MyPyramid emphasize people should eat, and what types does it attempt to deter people from eating?
9. How much poultry, red meat, flour and cereal products, vegetables, and fruit does the average American consume each year?
10. How has the overall American diet changed since 1970?
11. What are the primary grains consumed in the United States, and in what form are they consumed?

12. Discuss the differences between oils and fats, where they come from, and how their consumption has changed.
13. Which sweeteners are the most commonly consumed, and where do they come from?
14. The meat we consume comes from livestock. What are these animals primarily fed?
15. Discuss some of the many factors that affect the food we eat.
16. What is the most commonly used bioenergy crop grown today? Explain the process of its conversion into fuel.
17. Give an example of a cellulosic biofuel crop. Why is conversion of a cellulosic crop to ethanol more difficult than for a grain crop?

Critical Thinking

1. Keep track of what you eat tomorrow and then make a list of the ingredients in the food. What are the vegetables and field crops that contributed ingredients to your food? If you ate a meat product, consider what foods the cattle, poultry, or pork were fed.
2. Review what you ate today and determine if you are getting your daily servings of each food group. Are you avoiding the categories that the food pyramid discourages? Write a short essay analyzing your diet and think of some ways in which you could eat healthier.
3. Compare the most recent food guidelines (http://www.choosemyplate.gov/) developed by the USDA with the previous food pyramid. Which seems more beneficial to you? Do you think the government should be giving dietary advice to citizens?
4. Food costs in the United States are among the lowest in the world. What are some of the hidden costs? Are you willing to pay more for food?
5. Locate a biofuel plant near your location. Which crop(s) provides the raw materials? Why do you think this crop was chosen?
6. The United States is one of the leading producers of ethanol fuel from corn grain. Do you think we should continue increasing production?
7. Go to The BioFuels Atlas of NREL (http://maps.nrel.gov). With this interactive map, determine the production of crop biomass in your state and locate facilities for conversion of crops to energy.

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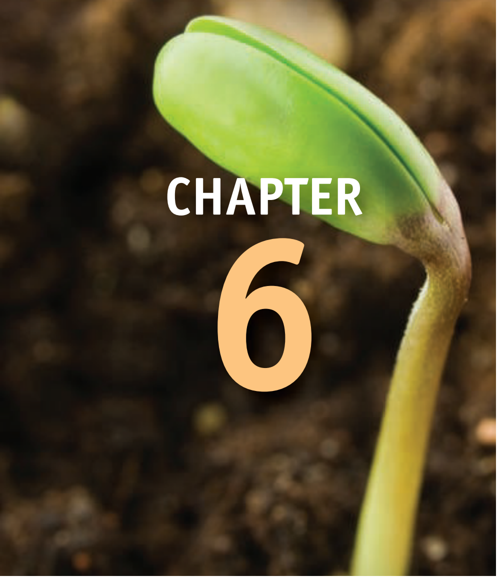
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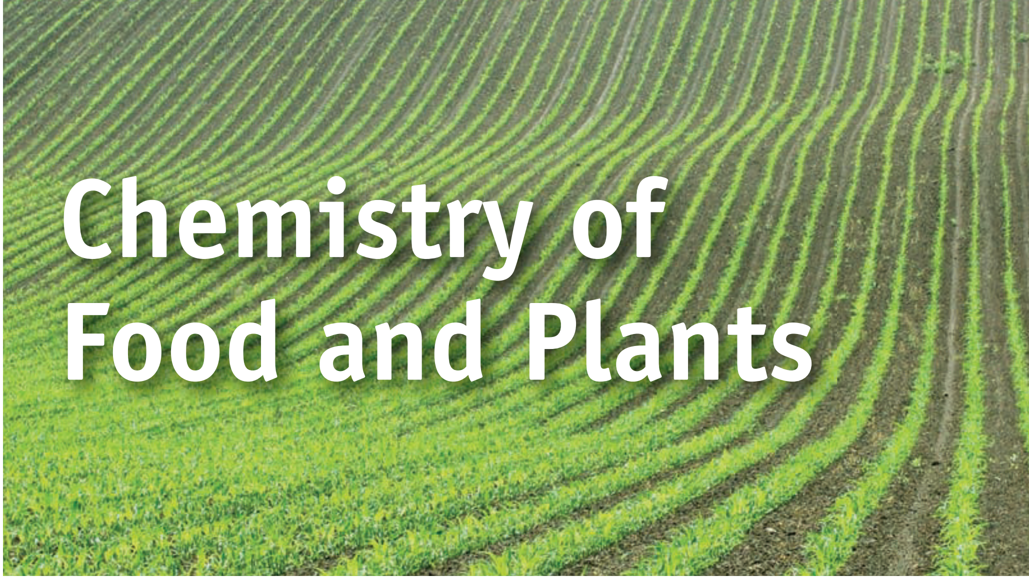
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CHAPTER

6



Chemistry of Food and Plants





Key Concepts

- All living organisms and nonliving materials are made of elements that join together to form compounds.
- Carbohydrates, proteins, lipids, and water are the important compounds in plants and animals.
- Carbohydrates are formed in plants during the process of photosynthesis and exist as monosaccharides, disaccharides, and polysaccharides.
- Proteins are compounds of amino acids and function in enzymatic reactions, structure, transport, and hormones.
- There are three major types of lipids: simple lipids, phospholipids, and steroids.
- Fats are lipids that are solid at room temperature, and oils from plants are liquid at room temperature.
- Vitamins and minerals have essential roles in plants and humans.
- Water is essential for all life on the earth. Its essential roles in plants include transport of nutrients, cooling, and as a solvent.

Key Terms

amino acid
atom
atomic number
carbohydrate
cellulose
cholesterol
disaccharide
element
fat
fiber
fructose
glucose
glycogen
high density lipoprotein (HDL)
high fructose corn syrup
inulin
lactose
limiting amino acid
lipids
low density lipoprotein (LDL)
maltose
mineral
monosaccharide
oil
omega-3 fatty acid
phospholipid
polysaccharide
protein
ruminant
saturated fatty acid
starch
sucrose
trans fatty acid
unsaturated fatty acid
vitamin
water
wax

Introduction

In the previous chapter we discussed the subject of food. Food comes in many forms and as many products. Although we have many social reasons to consume food, its potential to supply energy and nutrients is most important. Carbohydrates, protein, lipids, vitamins, minerals, and water are compounds essential for human nutrition. Humans obtain these nutrients from consuming plant products or by consuming meat from animals that have been fed plants. Carbohydrates, protein, lipids, and vitamins are biochemicals synthesized by plants from elements taken from the air and water.

Elements

All living organisms and nonliving materials such as rocks, minerals, and wood are made of **elements**. More than 100 elements exist in our world, but only 91 occur naturally. Elements are identified using chemical symbols such as C (carbon), O (oxygen), and H (hydrogen). The periodic table lists elements in order of increasing atomic weight (weight of an atom). Elements within the same family (elements in the same column) or periods (elements in the same row) have similar chemical properties (Figure 6-1).

Elements such as carbon, hydrogen, and oxygen are composed of a collection of atoms. **Atoms** are the smallest components of an element (Figure 6-2). Atoms consist of a nucleus made up of particles called *protons* and *neutrons*, as well as *electrons* that constantly circle the nucleus. Atoms of different elements differ in weight and in number of protons and electrons. Elements are assigned an **atomic number** based on number of protons. For example, hydrogen (H) has 1 proton and the atomic number of 1, whereas nitrogen (N) has 7 protons and the atomic number of 7. Because electrons do not contribute significant weight, atomic weight is based on the combined weight of the neutrons and protons in the nucleus. Electron numbers and energy levels mostly determine atoms' reactivity.

The most common elements in the nonliving portion of the earth's biosphere, in the human body, and in plants are shown in Table 6-1. The high silicon, iron, aluminum, and calcium concentration in the biosphere reflects the origins of the earth. Humans and plants contain significantly more oxygen and carbon than does the abiotic portion of the earth. Oxygen, carbon, hydrogen, and nitrogen constitute about 96 percent of the earth's total mass.

Atoms of different elements combine to form compounds. We will discuss in more detail some important compounds related to plant growth and human nutrition including the following:

- *Carbohydrates:* Compounds composed of carbon, oxygen, and hydrogen
- *Proteins:* Compounds composed of nitrogen, hydrogen, oxygen, and carbon
- *Lipids:* Compounds composed of carbon, oxygen, and hydrogen
- *Water:* Compound composed of hydrogen and oxygen

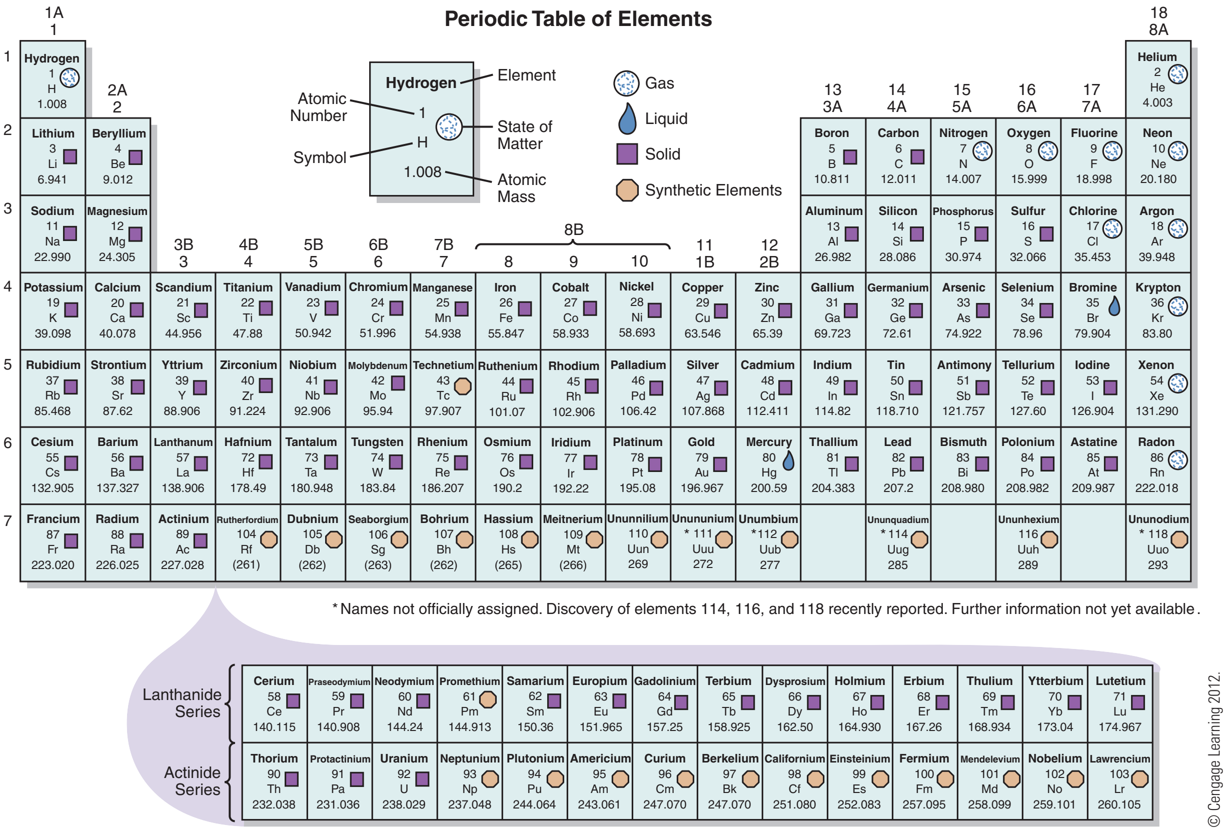


FIGURE 6-1 The periodic table showing all the elements. The elements are arranged in increasing order of atomic number from left to right across the table. The horizontal rows are called periods, and the vertical rows are groups. Most of the elements from 90 to 103 do not occur naturally.

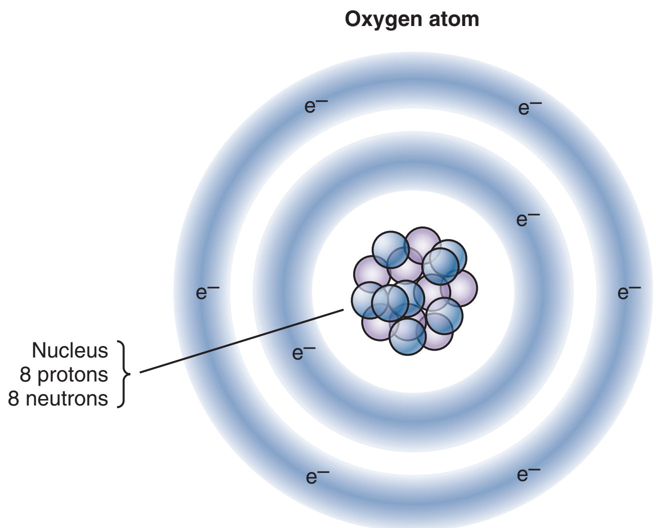


FIGURE 6-2
An oxygen atom. An atom consists of a nucleus of an equal number of protons and neutrons. Constantly moving electrons surround the nucleus.

TABLE 6-1

Elemental composition of the nonliving abiotic earth's crust, the average human body, and the average plant, all on a dry-mass basis.† *Adapted from Lutgens and Tarbuck (2000), Barden et al. (1987), and Whitney and Rolfes (2005).*

Element	Symbol	Abiotic earth	Human body	Plant
Oxygen	O	46.6	65	45
Carbon	C	<0.1	18	44.5
Hydrogen	H	1	10	6
Nitrogen	N	<0.1	3	1.5
Potassium	K	2.6	0.4	1
Calcium	Ca	3.6	1.5	0.5
Phosphorus	P	<0.1	1	0.2
Magnesium	Mg	2.1	0.1	0.2
Sulfur	S	<0.1	0.3	0.1
Iron	Fe	5.0	<0.1	<0.1
Silicon	Si	27.7	<0.1	<0.1
Aluminum	Al	8.1	<0.1	<0.1
Sodium	Na	2.8	<0.1	<0.1

†Expressed as a percentage of the dry weight (water removed). Plant elemental content is shown on a dry-matter and fresh-weight basis.

Carbohydrates

As their name implies, **carbohydrates** are compounds composed of carbon (C) hydrated with water (H_2O). In carbohydrates, carbon, hydrogen, and oxygen occur in the ratio of 1:2:1. Carbohydrates are the compounds in which the sun's energy is captured during photosynthesis. That process, as described in Chapter 8, can be seen in this simplified equation:

$$6\ CO_2 + 12\ H_2O + \text{sun energy} \longrightarrow C_6H_{12}O_6 + 6\ O_2 + 6\ H_2O$$

Carbohydrates are the most prevalent nutrients in plant structures and seeds, comprising 60–95 percent of the dry weight. Their purpose in plants is transferring and storing energy, as well as providing the structural skeleton of plants. Carbon compounds also provide the carbon skeleton for formation of other compounds such as amino acids, lipids, and hormones.

For humans, carbohydrates are an important source of energy in the diet, generally comprising more than half of the average caloric intake. Many of the calories in the human diet are derived from consumption of starch from grains such as corn, rice, and wheat; and from tubers and roots of potatoes, sweet potatoes, and yams. Others are consumed as sugar and fructose in fruits and as sweeteners in drinks and other products. Based on the number of basic units in each particular carbohydrate, they are classified as monosaccharides, disaccharides, and polysaccharides.

Monosaccharides

Monosaccharides, or simple sugars, are the basic building blocks of all carbohydrates, and they cannot be broken down into smaller compounds by reaction with water or human digestion (Figure 6-3). Sugars are soluble in water and are readily translocated through the vascular systems of plants and animals. Monosaccharides include glucose, fructose, and galactose. **Glucose** ($C_6H_{12}O_6$), also called *dextrose*, is the most abundant simple sugar. It is the first product of photosynthesis and is metabolized in plant and human cells to produce energy during respiration and glycolysis. Because body cells depend on glucose as a primary energy source, its regulation by the hormone insulin in the bloodstream is critical. Glucose is commonly found in fruits such as grapes and was once marketed for use as a low-cost, corn-syrup sweetener derived from processing corn grain (Figure 6-4). However, because its sweetening ability is only about three-quarters that of sucrose or fructose, glucose is not widely marketed as a sweetener today (Table 6-2).

Fructose is another common simple sugar. It has the same chemical makeup as glucose but a different structure. Fructose is the sweetest sugar and is naturally found in fruits and in honey (a mixture of fructose, glucose, and sucrose). **High fructose corn syrup** is a widely used, inexpensive sweetener. The average American now consumes about 60 pounds (27 kilograms) of high fructose corn syrup every year. It is the primary sweetener in sodas, fruit juices, candies, and processed foods. It helps breads to brown and can keep them soft. It also can reduce freezer burn in frozen products.

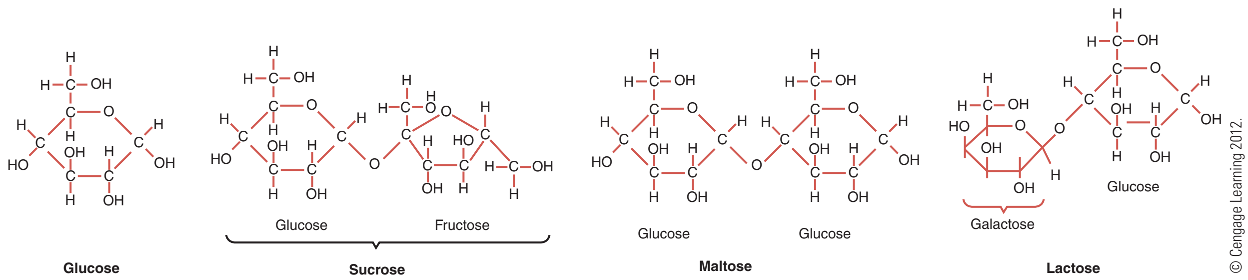


FIGURE 6-3 Molecular structure of glucose, sucrose, maltose, and galactose. Glucose is a monosaccharide. Galactose and fructose (shown as components of sucrose and lactose) are also monosaccharides. Sucrose, maltose, and lactose are all disaccharides. Maltose is composed of two glucose monosaccharides. Lactose is a milk sugar composed of galactose and glucose.



FIGURE 6-4
Corn grain. One bushel of corn can be refined to produce 33 pounds (15 kilograms) of sweetener, or nearly 5000 pounds per acre (900 kilograms per hectare).

TABLE 6-2

Relative sweetness of different sugars. The sweetness is measured as compared to sucrose (table sugar), which is rated as 100 on the scale. *Adapted from Belitz et al. (2009).*

Glucose	50 to 80
Fructose	110 to 170
Lactose	20 to 60
Galactose	30 to 50
Maltose	30 to 60
High fructose corn syrup (42% fructose)	80 to 90
Honey	95 to 105
Sucrose	100

High fructose corn syrup is a blend of fructose and glucose and is produced from corn syrup (which is primarily glucose). In the past, corn syrup was commonly formed from the processing of corn. However, it lacked the sweetness of sugar (sucrose). The process of producing high fructose corn syrup has several steps.

- Corn grain is mechanically processed to extract starch.
- Starch is enzymatically broken down by amylase to a corn sugar syrup consisting mostly of glucose.
- Glucose is enzymatically treated with glucose isomerase to form a mixture containing about 42 percent fructose.
- The 42 percent fructose-glucose mixture is then separated and filtered to increase the fructose proportion until it predominates.

Some consumers and health professionals are concerned about the impact that the widespread use of high fructose corn syrup has on human health. Consumption of high fructose corn syrup rose from less than 10 pounds (4.5 kilograms) per year in 1976 to 53 pounds (24 kilograms) in 2008, coinciding with increasing obesity rates. According to the Center for Disease Control (CDC), obesity rates in the United States rose from 15 percent in 1976 to over 30 percent in 2009. Some believe there may be a relationship between consumption of high fructose corn syrup and obesity. However, other health professionals believe that high fructose corn syrup is just one of many factors that affect obesity. Because of some of the negative public perceptions of high fructose corn syrup, the Corn Refiners Association recently requested permission from the USDA to use the name "corn sugar" instead of high fructose corn syrup.

Disaccharides

Disaccharides include sucrose, maltose, and lactose (Figure 6-3). They are compounds of two of the three monosaccharides described previously in this chapter. All disaccharides have the molecular formula $C_{12}H_{22}O_{11}$. They must be broken down into monosaccharide units before being metabolized in cells. **Sucrose** is the



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FIGURE 6-5
Products composed of disaccharides, as shown in the granulated sugars, and monosaccharides, as shown in the syrups.

most important disaccharide and is composed of about 50 percent glucose and 50 percent fructose. Sucrose has historically been the most widely used sweetener in the world. It is known as table sugar or simply as sugar (Figure 6-5). People in the United States consume about 60 pounds (27 kilograms) of sucrose annually. It is used as an additive to many foods and candies and is sold in granular form. Sucrose is extracted and refined from sugarcane and sugar beet. These plants store energy as sucrose. Sucrose is soluble in the water of the vascular system of plants and is the principal carbohydrate used for energy transfer within the plant.

Maltose is a disaccharide of two glucose molecules that is found most frequently in germinating grain seeds during the enzymatic breakdown of starch. This disaccharide is then further broken down into glucose that is used for energy production by the germinating seed. Maltose (malt sugar) is a product of the malting process associated with beer production; maltose is fermented to produce alcohol. The distinct taste of certain alcoholic beverages is associated with malt characteristics of the particular grain that is fermented. Malt was at one time widely used to sweeten milkshake beverages and is still a component of some candies such as malted milk balls.

Lactose is a disaccharide of glucose and galactose found in human and cow's milk. It is much less sweet than sucrose, but accounts for about half of the calories in cow's milk. A large proportion of the world's population experiences digestive upset because of being lactose-intolerant or of being unable to digest lactose. However, the majority of the U.S. population is not lactose-intolerant.

Polysaccharides

Polysaccharides can consist of many monosaccharide units joined together (Figure 6-6). Polysaccharides can store energy or function as structural compounds. Starch and inulin are polysaccharides found in plants, whereas glycogen is a storage carbohydrate found in animals. In plants, reserves stored as polysaccharides can be broken down to provide energy during times of dormancy, or to supply energy for germinating seed. The primary structural polysaccharide is cellulose (Figure 6-7). Other structural polysaccharides include hemicellulose (composed of xylose, manose, and galactose) and pectin (composed of galactose).

Starch, a glucose polymer, is the most widely consumed carbohydrate in human diets. It is the principal storage carbohydrate found in seeds or grains of grasses such as corn, wheat, and rice; in the grain of legumes such as soybean; in the tubers of potatoes and cassava; and in roots of alfalfa and sweet potatoes. Amylose and amylopectin are two forms of starch (Figure 6-6). Amylose is linear and relatively short chained, whereas amylopectin is branching and can contain

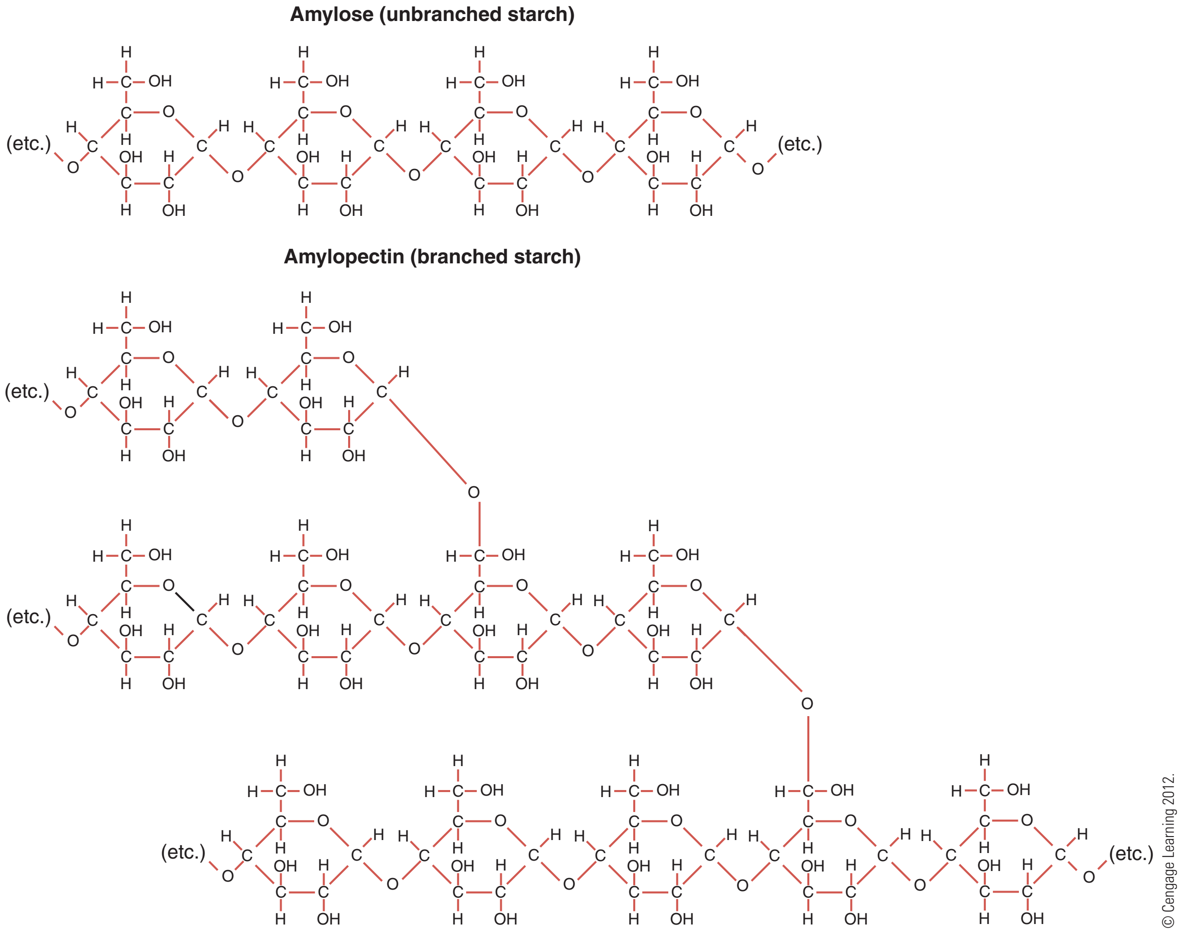


FIGURE 6-6 Starch is a polysaccharide of glucose and has unbranched (amylose) and branched (amylopectin) forms.

several thousand glucose units. When we consume starchy foods such as bread and potatoes, enzymes called *amylases* break starch down into glucose. Glucose is absorbed and translocated to cells in our bodies. Starch is widely used as a thickener in the food industry and as an adhesive.

Starch in grains has historically been used to produce ethanol for human consumption as beers and distilled liquors. In this process, the starch is broken down into glucose, which is then fermented by yeast. Today, plant-based biofuels are used to a limited extent as a replacement for petroleum-based fuels. Corn starch is now being converted to ethanol on an industrial scale. This ethanol is blended with gasoline and used as fuel for internal combustion engines.

Inulin is a unique polysaccharide of fructose. It is the primary storage carbohydrate in roots and tubers of plants such as dandelion, Jerusalem artichoke tuber, and chicory. Roots of these plants can be roasted and consumed by humans. Chicory roots are roasted and made into a caffeine-free coffee substitute.

Cellulose is a very long-chained glucose polymer important in the structural support of plants (Figure 6-7). Along with lignin, hemicellulose, and pectins, cellulose is a component of plant cell walls. Within plants, cellulose is the primary reservoir for carbon that is captured in photosynthesis. Cellulose often contains more than 50 percent of a plant's total carbon. The proportion of cellulose is

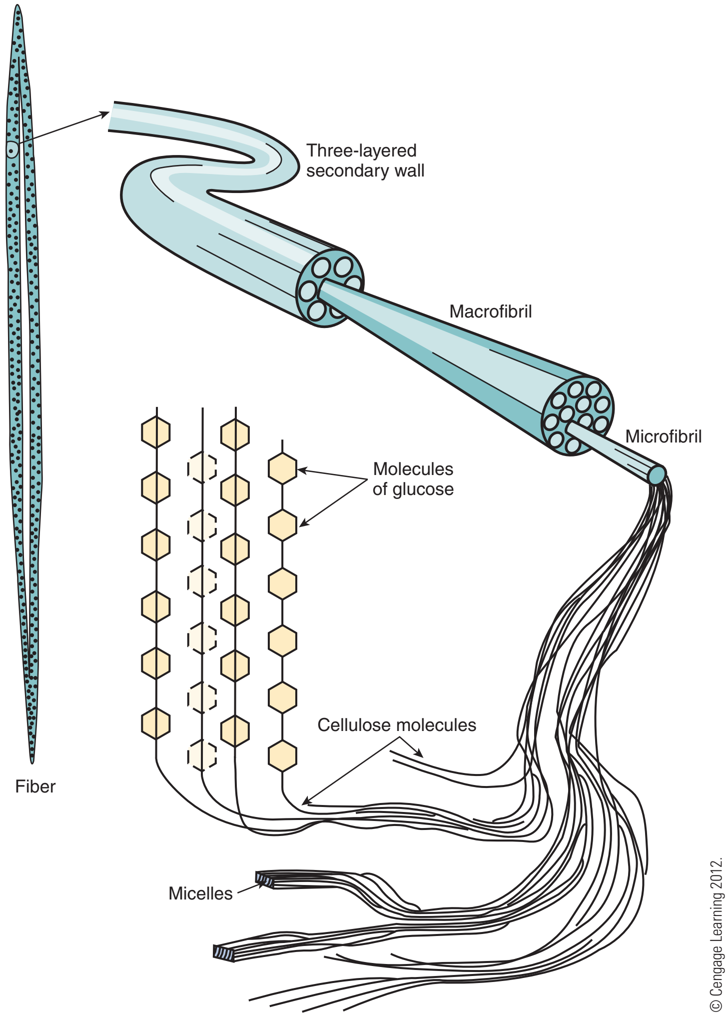


FIGURE 6-7
Cellulose is a polysaccharide composed of glucose and is important in the structure of plants. Individual cellulose chains are arranged together in microfibrils and fibers. The cellulose is often linked to lignin and hemicellulose to provide increased support.

greatest in the vegetative or woody proportion of plants and least in grains. Like starch, cellulose is made of long chains of glucose. However, the bonding between the glucose units differs so that humans and other animals such as swine cannot digest cellulose into glucose units. Therefore, it is unavailable to humans as an energy source, but animals such as cattle, sheep, and horses have specialized digestive systems containing microbes that can break down cellulose. Forages such as alfalfa and perennial grasses are a rich source of cellulose for livestock rations. Cellulose can also be converted to ethanol by fermentation.

Cellulosic biofuels along with starch-ethanol biofuels are potential replacements for gasoline. For cellulosic biofuels, cellulose is broken down into glucose that is subsequently fermented into ethanol. However, because of the complex linkages of cellulose with lignin and hemicelluloses, this conversion process is currently inefficient. The development of efficient pretreatment processes to break down lignin will be important in making the cellulosic ethanol production cost effective.

Mature grasses such as switchgrass (Figure 6-8) and smooth bromegrass can produce significant amounts of biomass for livestock consumption or ethanol production. Potential yields in the Midwest are 6 tons/acre (12,000 kilograms/hectare). When harvested in late autumn, switchgrass contains about 40 percent



FIGURE 6-8
Switchgrass is a native species used for ethanol production or livestock consumption.

cellulose, 30 percent hemicellulose, and 20 percent lignin. The presence of lignin affects the availability of cellulose and hemicellulose for digestion.

Glycogen is the only carbohydrate made in animals. It is a long-branched chain polymer of glucose. Glycogen is stored in the liver or muscle, and glucose can be rapidly released when a need for energy arises.

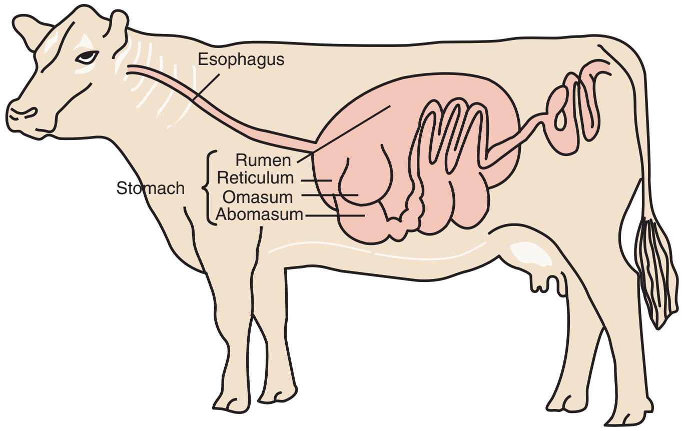
Ruminants

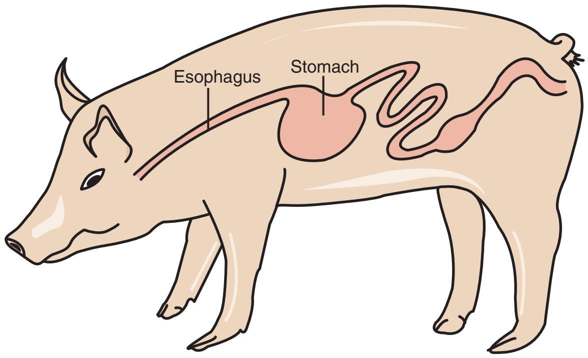
Cattle, sheep, goat, and deer are **ruminants**, an animal group that can use cellulose. Ruminants are a type of animal with a four-chambered stomach that includes the rumen, reticulum, omasum, and abomasum (Figure 6-9). The rumen is a large fermentation vat that contains bacteria populations capable of converting cellulose and other less complex carbohydrates to volatile fatty acids (VFA). VFA enter the bloodstream and are the primary energy source for ruminants. Horses are not ruminants, but they still can digest cellulose because they have a large cecum, a fermentation vat within the large intestine. Humans, swine, dogs, and cats are monogastrics (one stomach) and cannot use cellulose as an energy source.

Ruminants play a unique role in worldwide food systems, because they can use vegetative plant materials or forages that humans cannot digest. Often forages are the only crops that can be grown in extreme climates or on steep lands with poor soils. Before domestication, ruminant animals subsisted entirely by grazing and browsing of vegetative materials such as grasses. In modern meat- and milk-production systems, they are often fed high-energy grain feeds such as corn to enhance the rate of meat and milk production.

Fiber

Fibers are associated with the structural parts of plants. The human digestive system does not break them down. Because of the association of fiber with reduced incidence of colon cancers and heart disease, many dieticians encourage people to increase their dietary fiber intake. Labels on foods must indicate dietary fiber levels (see Chapter 5). Fibers can be generally categorized as soluble and insoluble.





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FIGURE 6-9
A cow is a ruminant that has a specialized four-part stomach. The largest part, the rumen, contains bacteria that can ferment cellulose. In contrast, swine are called monogastrics and have a simple digestion system incapable of fermenting cellulose.

- Pectins and gums are soluble fibers that form gels and are fermented in the intestinal tract. Pectins are found in citrus fruits, apples, and vegetables. Dietary pectin levels are associated with reducing blood cholesterol and blood glucose levels. The gel-forming properties of pectins also make them useful in jellies. Pectins are polysaccharides of galactose. Gums are polysaccharides chemically related to pectins but with a different composition. They are found in legume seeds. The most common gum source is gum arabic collected from the bark of the gum acacia tree, which is indigenous to Africa. Gum arabic is used in chewing gum and as an emulsifier and stabilizer in beverages and other foods. Pectin and gums are water-soluble dietary fiber important in reducing blood cholesterol levels.
- Cellulose, hemicellulose, and lignin are insoluble and indigestible fiber components that stimulate the intestinal tract. These are primary components of forage crops, but—in terms of the human diet—are most often found in whole grains and fruits.

Proteins and Amino Acids

Proteins are major components of all organisms. Proteins have several essential roles in animals and plants.

- *Enzymes:* catalyze biological reactions and digestion
- *Structural:* a component of muscles and tendons

- *Defense:* a component of antibodies that provide immunity against disease
- *Transport:* a component of hemoglobin, a transporter of oxygen in the bloodstream
- *Hormones:* regulate metabolic activity in the body
- *Storage:* storage of amino acids in seeds

Proteins are composed of molecules called **amino acids** (Figure 6-10). Most proteins are very large. Amino acids have a common structure consisting of a central carbon (C) with a hydrogen (H), an amino group (NH_2), and a carboxyl group (COOH). Amino acids differ from one another by the side group attached to the C atom. Some amino acids also contain sulfur and phosphorus.

Twenty amino acids are used for protein synthesis. Plants can make all of these from carbon captured during photosynthesis, in addition to nitrogen and sulfur taken up from the soil. In contrast, humans can synthesize only 11 of these amino acids in their bodies, and nine must come from the diet (Table 6-3). These nine are called *the essential amino acids*.

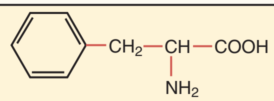
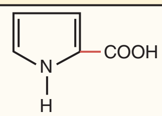
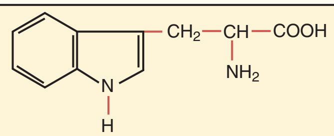
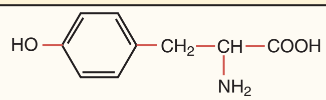
Name	Formula
Lysine	$H_2N{-}(CH_2)_4{-}CH(NH_2){-}COOH$
Methionine	$CH_3{-}S{-}(CH_2)_2{-}CH(NH_2){-}COOH$
Phenylalanine	
Proline	
Serine	$CH_2(OH){-}CH(NH_2){-}COOH$
Threonine	$CH_3{-}CH(OH){-}CH(NH_2){-}COOH$
Tryptophan	
Tyrosine	
Valine	$CH_3{-}CH(CH_3){-}CH(NH_2){-}COOH$
Isoleucine	$CH_3{-}CH_2{-}CH(CH_3){-}CH(NH_2){-}COOH$
Leucine	$CH_3{-}CH(CH_3){-}CH_2{-}CH(NH_2){-}COOH$

FIGURE 6-10
Structural makeup of diverse amino acids.

TABLE 6-3

Essential and nonessential amino acids. Twenty naturally occurring amino acids combine to make different proteins.

Essential amino acids	Nonessential amino acids
Histidine	Alanine
Isoleucine	Asparagine
Leucine	Aspartic acid
Lysine	Arginine
Methionine	Cystine
Phenylalanine	Glutamic acid
Threonine	Glutamine
Tryptophan	Glycine
Valine	Proline
	Serine
	Tyrosine



Limiting Amino Acids

The seed of corn is typically deficient in the essential amino acid tryptophan and soybean is deficient in methionine (Table 6-4). When one essential amino acid is deficient relative to the other essential amino acids in a food source, it is called a **limiting amino acid** because it restricts the total amount of protein that can be obtained. Animal protein sources such as meat contain all the essential amino acids, but most plant protein sources are low in one or more of the essential amino acids. Nutritionists compare protein sources by assigning a protein score. Chicken eggs contain the essential amino acids at a level to meet all human needs and are assigned a score of 100. Protein sources with scores of less than 70 are unsatisfactory on their own to meet human needs. Vegetarian diets that depend on plant grains as a source of protein must be planned to include protein from foods with different amino acid profiles. An example diet would consist of tofu from soybean as well as a corn dish.

A striking example of the effect of protein deficiency on human health is the disease *kwashiorkor* in small children. The disease has most often been documented in developing countries such as those in Africa. Kwashiorkor symptoms include a swollen abdomen and puffy skin, and they occur most often in infants who have diets high in calories but low in protein. The symptoms can be reversed if a protein-rich diet is fed, but the condition can also become chronic and involve mental retardation.

TABLE 6-4

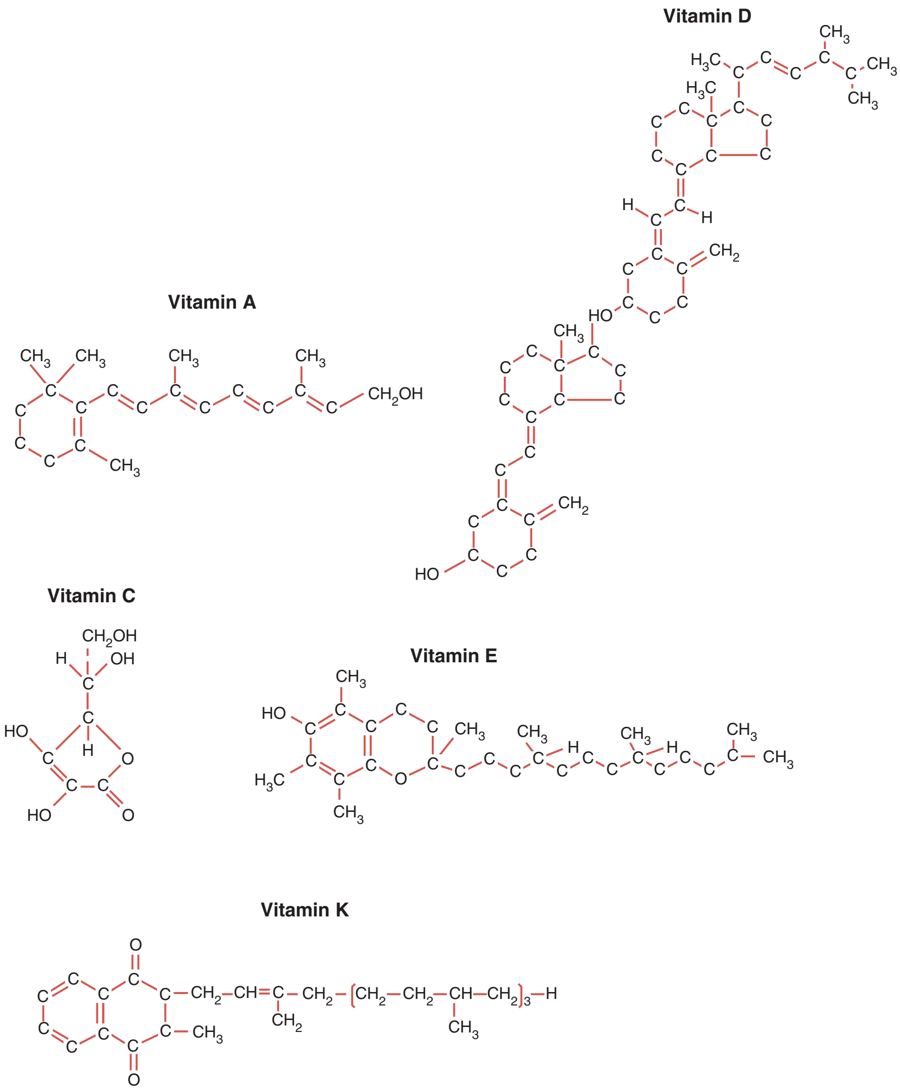
Essential amino acids in selected foods. Amounts are expressed as milligrams of amino acid per gram of protein nitrogen. Eggs are considered to have perfect protein, and other foods are rated in comparison with eggs to give a protein score. *Adapted from Food and Agriculture Organization (1970).*

Food	Isoleucine	Leucine	Lysine	Methionine	Phenylalanine	Threonine	Tryptophan	Valine	Protein score
Eggs	393	551	436	210	358	320	93	428	100
Beef	301	507	556	169	275	287	70	313	80
Cow's milk	295	596	487	157	336	278	88	362	79
Chicken	334	460	497	157	250	248	64	318	72
Fish	299	480	569	179	245	286	70	382	70
Corn	230	783	167	120	305	225	44	303	49
Wheat	204	417	179	94	282	183	68	276	62
Rice	238	514	237	145	322	244	78	344	69
Beans	262	476	450	66	326	248	63	287	44
Soybeans	284	486	399	79	309	241	80	300	67
Potatoes	236	377	299	81	251	235	103	292	34

Vitamins

Vitamins are small, organic compounds that are important in regulation of metabolism. These were first identified using letters of the alphabet (A, B, C, D, E, and K) and also by subcategories such as B_1, B_2, and B_3. The vitamins also have common names such as riboflavin (B_2) and thiamine (B_1). They have diverse chemical structures (Figure 6-11). Some vitamins act in metabolic reactions to promote the function of essential enzymes, whereas others are antioxidants. Humans require 13 essential vitamins that must be obtained from the diet (Table 6-5).

Vitamin D can be synthesized by humans upon exposure to sunlight. Vitamins are required in small amounts (i.e., milligrams or less), but deficiencies can cause some unique symptoms with some historical significance.



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FIGURE 6-11
These essential vitamins have distinct chemical structures.

TABLE 6-5

Vitamin deficiencies can cause a wide range of health problems. *Adapted from Levetin and McMahon (1996) and Janick et al. (1981).*

Vitamin	Dietary sources	Deficiency symptoms
Vitamin A	Meats, dairy, green vegetables, carrots, tomatoes, squash	Night blindness, eye inflammation
Vitamin D	Oily fish, fortified dairy products; the body also produces it when skin is exposed to sunlight	Rickets (softening of the bones)
Vitamin E	Vegetable oils, green leafy vegetables, grains, meat, dairy	Anemia in premature babies
Vitamin K	Spinach and other green leafy vegetables, tomatoes, vegetable oils	Increased clotting time of blood
Thiamine (Vitamin B_1)	Whole cereal grains, legumes, nuts, meat, dairy	Beriberi (a nervous system ailment)
Niacin (Nicotinamide)	Turnip greens, peanuts, meat	Pellagra (diarrhea, dermatitis, dementia)
Riboflavin (Vitamin B_2)	Green vegetables, whole wheat flour, meat	Dermatitis, anemia
Pyridoxine (Vitamin B_6)	Peas, beans, milk, meat	Dermatitis, increased susceptibility to infections
Pantothenic acid	Fruits, peas, cabbage, meat, dairy	Gastrointestinal disturbances
Folic acid	Legumes, green leafy vegetables, whole grains	Anemias, fatigue
Cyanocobalamine (Vitamin B_{12})	Meat, dairy	Pernicious anemia
Biotin	Peanuts, dairy	Dermatitis
Ascorbic acid (Vitamin C)	Citrus fruit, vegetables, potatoes	Scurvy

Vitamin C (ascorbic acid) deficiency can cause scurvy. Symptoms include hemorrhaging in the gums and skin, poor wound healing, and death. Prior to the twentieth century, scurvy was a particular concern for sailors and travelers on extended voyages where the diet was primarily meat and bread. Eventually, it was discovered that scurvy could be effectively prevented or treated with dietary supplements of citrus fruits. On the voyage of the *Mayflower* in 1620, Pilgrims consumed onions and lemons to prevent scurvy.

Deficiency in Vitamin B_1 (thiamine) causes beriberi. Symptoms include physiological disorders, muscle weakness, enlarged heart, and death. Vitamin B_1 is present in the bran and endosperm of grains; milling to remove the bran and endosperm produces a grain lacking the vitamin. Beriberi has been a worldwide problem in diverse cultures. For example, it was observed in colonial America when white bread was favored over whole grains and in Asian populations when

Careers in Food Science

Careers in food science are great opportunities to work in many aspects of food processing including: developing new nutritious food products, monitoring the microbiological safety of foods, and packaging foods. Students who prepare for a career in food science study chemistry, microbiology, physics, and engineering.

Chemistry—Food scientists study properties of proteins, fats, starches, and carbohydrates, as well as additives and flavors, to determine how each works in a food's preparation and storage. They develop ways to use new ingredients to enhance food nutritional value.

Microbiology—Microbiology is an important part of food science because many foods like bread and cheese are made by microorganisms like yeast and fungi. Microorganisms are responsible for food spoilage. Microbes like *E. coli* and *Salmonella* are responsible for serious food-borne human illness. Food scientists are studying ways to monitor and detect these organisms in food.

Physics and engineering—The modern food system involves handling and processing of food from diverse sources. Systems must be optimized to economically produce safe, wholesome, and value-added products. Food scientists study packaging, handling, and storage of foods. Foods must be packaged to protect food and aid in marketing to consumers.

Food scientists can make substantial contributions to society. One example is Lester Borchardt (1908–2007), a food scientist specializing in food processing at General Mills. Using his physics background, he developed the technologies to create Cheerios in 1941, which involved inventing an "air gun". The new product was first marketed as "CheeriOats", the first oat-based, ready-to-eat cold cereal. He was also involved in the creation of several other breakfast cereals. Later, Borchardt developed the process to fortify milk with Vitamin D. This development was significant, not only because Vitamin D aids in absorbing calcium in milk, but also because Vitamin D can be difficult to obtain through other dietary sources. This advance is credited with reducing the occurrence of rickets, caused by lack of Vitamin D. Borchardt, who lived to be 99, ate a bowl of Cheerios with milk every day.

polished white rice replaced whole grain rice. American prisoners of war (POWs) of the Japanese in World War II, who were generally malnourished, also exhibited symptoms of beriberi when white rice was their only food source.

Plants can synthesize most of the important vitamins except Vitamin D. Dieticians recommend a varied diet that includes vegetables, fruits, and whole grains to obtain many of the necessary vitamins. Meats are also good sources of several vitamins. Many processed foods, breads, and milk are now fortified with vitamins.

Lipids (Fats and Oils)

Lipids are a group of organic compounds that are insoluble in water. They are a concentrated source of energy and also play critical functions in both plants and animals. Relative to carbohydrates, lipids provide 225 percent more energy per gram. Animals use lipids as the primary form of energy storage. As a food, they are an important energy source for humans and carnivores within ecosystems (Figure 6-12). There are three major types of lipids: simple lipids, phospholipids, and steroids.

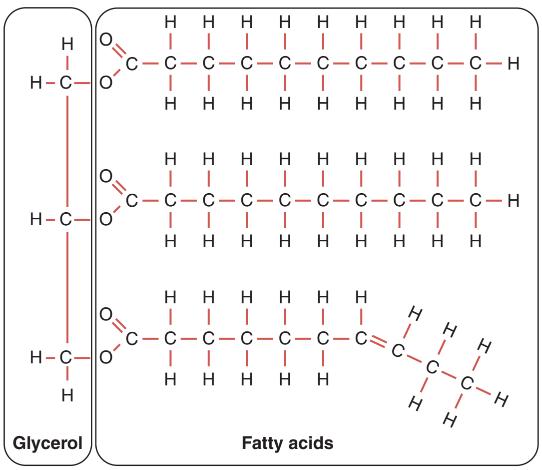
Simple Lipids

Simple lipids such as fats and oils are the most abundant types of lipids. Lipids from animals are called **fats** and are solid at room temperature. Lipids from plants are called **oils** and are liquid at room temperature. Both are chemically described as triglycerides formed from three fatty acids and an alcohol, glycerol (Figure 6-13). Fatty acids are mostly 18-carbon long fatty acids but some may have 24 carbons. The term *fatty acid* is widely used in the popular press today. There are different categories of fatty acids (Figure 6-14):



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FIGURE 6-12
A variety of lipids derived from plant sources. Oils are extracted from crops such as corn, soybean, canola, and flax. Oils are unsaturated and liquid at room temperature. Subjecting oils to heat and injecting hydrogen transforms oil to a solid form. This process makes margarine that is solid at room temperature.



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FIGURE 6-13
Generalized structure of a triglyceride, a common form of lipid. Triglycerides are formed from glycerol and three fatty acids that differ in length and degree of saturation.

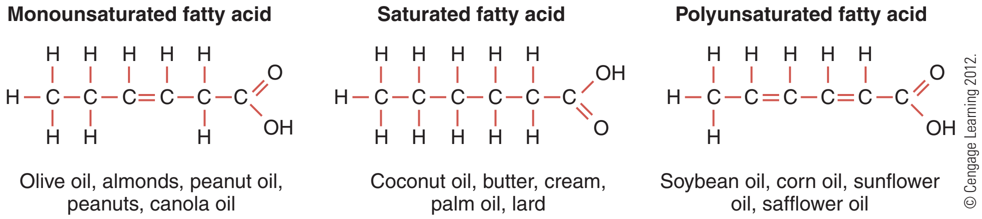


FIGURE 6-14 Three categories of fatty acids and their sources. These categories are based on the number of double-carbon bonds within the carbon chain.

- **Saturated fatty acids** are long-chain fatty acids with all single bonds between the carbon atoms. They are saturated with hydrogen. Animal fats are typically all saturated.
- **Unsaturated fatty acids** are long-chain fatty acids that have one or more double bond between the carbon atoms. These fatty acids come from plants, although some plants can contain saturated fatty acids. Monounsaturated fatty acids have only one double-carbon bond, whereas polyunsaturated fatty acids have two or more. The predominant polyunsaturated fatty acids are linoleic and linolenic acids, which are 18 carbons long. Canola oil and olive oil contain oleic acid that is a monounsaturated fatty acid (one double bond).
- **Trans fatty acids** are long-chain fatty acids that have been partially hydrogenated (adding hydrogen [H] under heat and pressure). Therefore, polyunsaturated oils are made more saturated. Hydrogenation can convert vegetable oils from liquid to solid or reduce the rancidity potential of oils, which increases shelf life. Many of the margarine and cooking oils sold today and used in fast-food establishments are made from transformed oils extracted from corn or soybean.

Other kinds of simple lipids are waxes. **Waxes** are the shiny coatings on some leaves and fruits. Waxes protect the outside of leaves and fruits and reduce water loss. When you polish an apple, you are shining the waxy coating. Bees making honeycomb also produce waxes.

Complex Lipids

There are several types of complex lipids including phospholipids and steroids. **Phospholipids** are essential components of the membranes in plants. Both phospholipids and steroids are components of membranes and liver, brain, and spinal tissue in humans.

Cholesterol is a steroid lipid in animals that is essential for membrane, hormone, and brain- and nerve-tissue formation (Figure 6-15). Meats, eggs, butter, and cheeses are high in cholesterol. The human body also synthesizes cholesterol. High levels of cholesterol are the leading cause of heart disease due to arteriosclerosis, or blockage of the arteries.

If you have a blood cholesterol test, most reports will come back with the following three numbers: total cholesterol; **high density lipoprotein (HDL)**; and

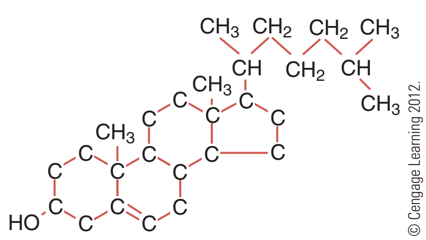


FIGURE 6-15 The structure of cholesterol.

low density lipoprotein (LDL). The HDL and LDL fractions represent complex compounds of cholesterol, lipids, and proteins that function in the transport and deposition of cholesterol. HDL is good because it removes excess cholesterol from the blood, whereas LDL is bad because it is associated with deposition of cholesterol in coronary arteries. Ideal levels of total cholesterol are 200 or less. HDL should be >40, whereas LDL should be <100–130.

If you have high levels of total cholesterol and LDL, you will be advised to modify your diet to consume fewer foods that are high in cholesterol and saturated fats. You will also be advised to consume more plant products that are high in unsaturated oils and fiber, because these are known to reduce blood cholesterol levels. The soluble fiber in some cereal grains such as oats have especially been associated with reducing cholesterol.

Lipids: Health Risks

Many in our society consume excessive quantities of lipids. This eating pattern may be related to the innate human attraction to the taste and smell of lipids. This attraction may have developed during times when high levels of energy intake were essential for survival. However, such high levels are unnecessary for most normal humans today.

Where do the lipids come from (Table 6-6)? A major source of lipids is the meat we consume such as steak, bacon, roasts, and burgers, which contain saturated fats and cholesterol. In addition, deep-fried foods such as french fries, fried

TABLE 6-6

Sources of saturated, monounsaturated, and polyunsaturated fatty acids. Group 1 has mostly saturated fatty acids, Group 2 has mostly monounsaturated fatty acids, and Group 3 has mostly polyunsaturated fatty acids. *Adapted from USDA-ARS (2007).*

		Percentage of total lipids (%)		
		Saturated	Monounsaturated	Polyunsaturated
Group 1	coconut oil	91.9	6.2	1.9
	butter	65.6	30.5	3.9
	beef tallow	52.1	43.7	4.2
	palm oil	51.6	38.7	9.7
	lard	41.0	47.2	11.7
Group 2	olive oil	14.2	75.0	10.8
	canola oil	7.4	61.6	31.0
	peanut oil	17.8	48.6	33.6
Group 3	safflower oil	6.5	15.1	78.4
	sunflower oil	10.5	20.5	69.0
	corn oil	13.6	29.0	57.4
	soybean oil	15.1	24.4	60.6
	cottonseed oil	27.1	18.6	54.3

chicken, and potato chips contain unsaturated vegetable oils absorbed during the cooking process. Though butter use has declined because of its saturated fat level, we now consume excessive amounts of margarines made from trans fatty acids. This eating pattern has several consequences.

- We are seeing a dramatic rise in obesity and Type 2 diabetes in children and adults partially because of excessive consumption of lipid energy. Lipids contain more than 225% the energy of protein and carbohydrates.
- Excess trans fatty acid consumption has been associated with a significant increase in heart disease. Trans fatty acids raise LDL cholesterol levels, while at the same time lowering HDL levels. Therefore, products must now be labeled to show trans fatty acid content. In addition, some cities have banned the use of trans fatty acids in commercial food preparation.
- Cholesterol, when in the form of LDL, is a primary factor in the incidence of heart disease due to arteriosclerosis.

Because it is unlikely that the American diet will evolve to be devoid of all lipids, healthy alternative dietary choices should be considered. Replacement of saturated fats and trans fatty acids with polyunsaturated and monounsaturated oils is recommended as a strategy to reduce heart disease.

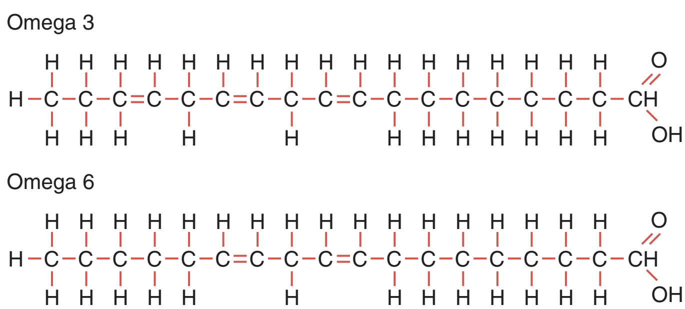
Essential Fatty Acids: Health Benefits

In contrast to health risks associated with excess lipid consumption, two fatty acids, linoleic and linolenic, are essential for the human diet because they cannot be made in the human body. Recently, **omega-3 fatty acids** such as linolenic acid have been shown to have significant health benefits such as:

- stimulation of brain and memory functions—high doses of omega-3 fatty acids have been used to treat depression bipolar disorder;
- lowering of blood pressure;
- preventing blood clots and reducing blood triglycerides.

The omega-3 designation relates to the chemical structure of the fatty acid (Figure 6-16). The typical American diet—based on corn and soybean with meat that is high in omega-6 fatty acids—actually depresses omega-3 fatty acid levels. Diets are therefore recommended that contain omega-3 rich foods and meats such as salmon, tuna, and sardines. Feeding animals flaxseed, a plant source, can increase the omega-3 fatty acid content of eggs and meats. Also, grass-fed beef cattle have more omega-3 fatty acids than cattle fed mostly corn and soybean diets.

FIGURE 6-16
Linolenic (omega 3) and linoleic (omega 6) are two essential polyunsaturated fatty acids. They are 18 carbons long and differ in the location of the first carbon double carbon double bond, counting from the CH_3 end of the chain.



Minerals

As discussed previously, carbon, oxygen, hydrogen, and nitrogen play critical roles as components of carbohydrates, protein, lipids, and other important compounds. They comprise more than 96 percent of the dry weight of animals and plants. Seventeen other additional mineral elements are essential for normal human growth and sustenance (Table 6-7), and 15 are essential for plants. **Minerals** are inorganic compounds that exist as free ions (positively or negatively charged atoms) and can be components of larger organic compounds such as hemoglobin, an important carrier of oxygen in the bloodstream. Humans can consume meats and plants to obtain many of these minerals. Depending on the amount needed in diets, minerals are categorized as macro minerals or micro minerals.

TABLE 6-7

Human dietary minerals and their function. *Adapted from Levetin and MacMahon (1996) and Whitney and Rolfes (2005).*

Mineral	Function
Macro minerals	
Calcium	Bone and tooth formation, muscle contraction
Phosphorus	Nucleic acids, bone and tooth formation, cell membranes, energy
Sulfur	Protein formation
Potassium	Muscle contraction, nerve transmission, electrolyte balance
Chlorine	Gastric juice
Sodium	Nerve transmission, body water balance
Magnesium	Protein formation, enzyme cofactor
Micro minerals	
Iron	Hemoglobin, a carrier of oxygen in the bloodstream
Zinc	Component of many enzymes
Iodine	Component of thyroid hormones
Fluorine	Bone and tooth formation
Copper	Enzyme component, red blood cell formation
Selenium	Antioxidant
Cobalt	Component of Vitamin B_{12}
Chromium	Normal glucose metabolism
Manganese	Enzyme cofactor
Molybdenum	Enzyme cofactor

Water

Water is essential for all life. Humans can survive for weeks without food but only days without water. Though plants are more adaptable to water deprivation, their survival too is limited without water. Water is critical because it comprises about 60 percent of the human body and as high as 90 percent of some plants. Chemically, water is H_2O. Hydrogen is bonded to oxygen, and water molecules are attached to form a liquid mass. Water exists in solid, liquid, and gaseous states. It is one of the few compounds that is less dense as a solid than as a liquid.

Water has an essential role as a solvent for many compounds. It dissolves salts such as sodium chloride. In plants, water carries minerals, sucrose, and hormones. The transpiration stream in plants is the main route for movement and uptake of minerals such as NO_3 (see Chapter 8). It provides turgor, or support for cells. Water evaporation from leaf and skin surfaces provides heat loss.

In humans, it is involved in excretion of waste products in urine. The average person needs to consume from one-half gallon (1.89 liters) to three-quarters gallon (2.84 liters) of water per day through food or beverages. Water loss without rehydration rapidly affects physical health.

Review Questions

1. What are the different components of an atom?
2. What are the most common elements found in plants, humans, and the earth's crusts, respectively?
3. What are carbohydrates? How are they formed in plants? What are the different types of carbohydrates?
4. What are monosaccharides? Give some examples.
5. Describe the chemistry of a commonly used disaccharide and its use.
6. What is high fructose corn syrup? Why is it so widely used, and in what types of products is it used?
7. What are the two general types of polysaccharides? Give an example and explain their chemical structure and function.
8. How does a ruminant animal differ from a monogastric animal in terms of digestive systems and in capacity to digest fiber such as cellulose?
9. What is the chemical difference between soluble and insoluble fiber?
10. What are proteins? How do plants and humans differ in their capacity to synthesize proteins?
11. Diets comprised exclusively of grains such as corn and wheat are likely to be deficient in what two amino acids?
12. What are vitamins and their functions? Which are essential to humans?
13. Describe what lipids are and give the three different types.
14. What is an omega-3 fatty acid, and what human health advantage do omega-3 fatty acids offer?
15. Why is water so important to all life? Discuss its role in plants.

Critical Thinking

1. High fructose corn syrup and trans fatty acids are widely used food additives that are made by humans. What are the pros and cons of using such products? Should we require that only natural ingredients be used in our foods?
2. Many students are challenged as they study the chemistry of elements and compounds. However, it is important to do so because these compounds are very relevant to our lives. Review the ingredients in one meal that you consume and describe the chemical compounds you are consuming.

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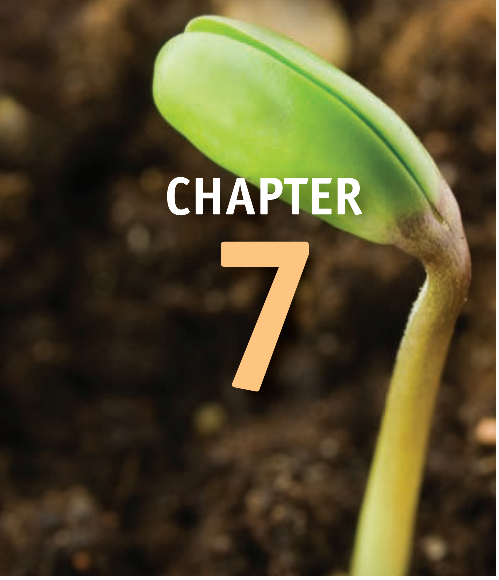
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CHAPTER 7



Plant Anatomy and Morphology





Key Concepts

- Monocots such as corn and wheat, and dicots such as soybean and cotton are two important groups of crop plants.
- Plants have four organs: roots, stems, leaves, and flowers. The form and function of these organs can vary among plants.
- Within plants' four organs, the tissues are vascular, meristem, epidermis, and ground tissue.
- Seeds are the fertilized ovules of the flower. They emerge from the soil and develop into mature plants.

Key Terms

adventitious root
anatomy
apical meristem
axillary meristem
blade
bulb
clone-former
collar
collenchyma
complete flower
compound leaves
cork cambium
corm
crown-former
determinate
dicot
dioecious plant
epidermis
epigeal
fibrous root system
flower
fruit
germination
ground tissue
hypogeal
imperfect flower
incomplete flower
indeterminate
inflorescence
intercalary meristem
internode
leaves
meristem
monoecious plant
monocot
morphology
node
parenchyma
perfect flower
petal
petiole
phloem
pistil
plant growth regulator
plant hormone
rhizome
root
sclerenchyma
secondary meristem
seed
sepal
sheath
simple leaves
stamen
stem
stolon
stomata
taproot
tiller
tuber
vascular cambium
venation
xylem

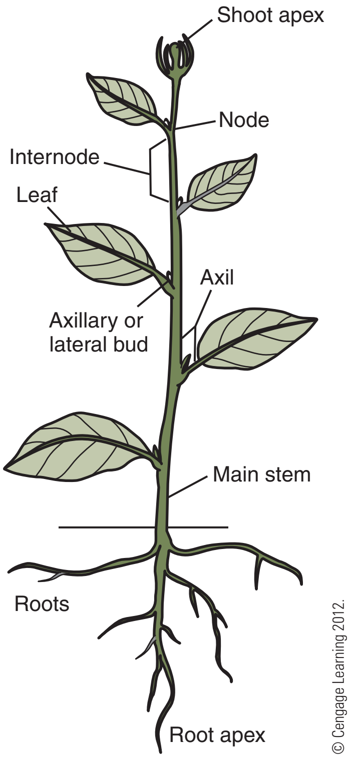


FIGURE 7-1
A dicot showing the leaves, stems, roots, nodes, and internodes.

Introduction

Plants are highly organized and contain many specialized organs and tissues. Understanding the anatomy and morphology of plants provides a foundation for understanding how plants look, grow, and ultimately produce food. It is also important in developing plant management and pest control strategies for optimizing crop yield. **Morphology** deals with the form and structure of plants. The plant morphological features we typically see are the flowers, roots, stems, and leaves (Figures 7-1 and 7-2). Plant **anatomy** is the study of the internal tissues and cells of plants. The epidermis, vascular system, meristems, and ground tissues are important types of tissues that are constructed of individual, specialized cells.

Monocots and Dicots

Monocots and **dicots** are two important groups of crop plants. The names monocot (one) and dicot (two) are derived from the numbers of cotyledons a plant has. Cotyledons are the first leaves formed in a seed. Though monocots and dicots have many of the same plant tissues, their anatomy and morphology differ (Table 7-1).

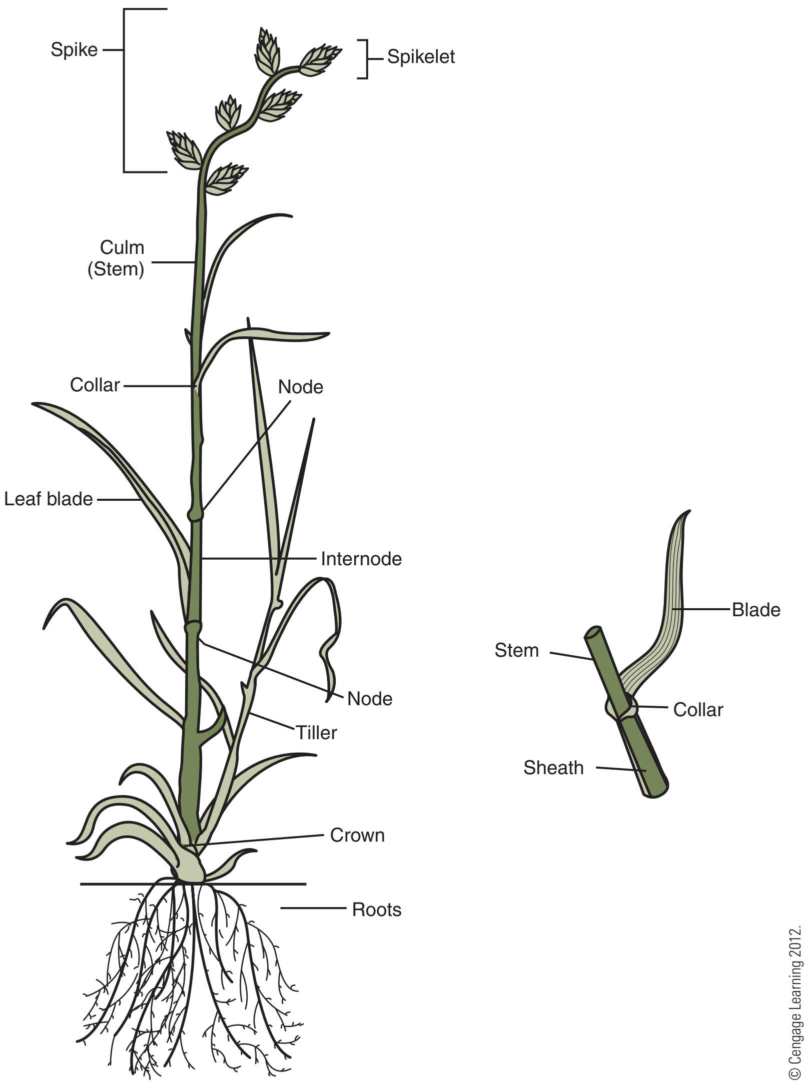


FIGURE 7-2
A monocot showing leaves, stems, roots, nodes, and internodes.

TABLE 7-1

Monocot and dicot characteristics.

Monocots (1 cotyledon)	Dicots (2 cotyledons)
Usually herbaceous	Herbaceous or woody
Linear leaves with parallel veins	Leaves with netted venation
Vascular bundles scattered in stem	Vascular bundles in a ring
Fibrous root system	Taproot system
Hypogeal germination	Usually epigeal germination
Examples include corn, wheat, and rice	Examples include soybean, cotton, and alfalfa

Plant Tissues

The tissues of a plant include the epidermis, xylem, phloem, ground tissue, and meristems. Each type of tissue has specific functions.

Epidermis

The **epidermis** is the outer, protective, cell layer on the stem and leaves. The epidermis is frequently covered by the cuticle, a waxy covering that reduces water loss and protects the tissues from attacks by parasites and predators such as fungi and insects (Figure 7-3). Many leaves and stems are covered with hairs or spines that offer additional protection for the plant and sometimes secrete chemicals to repel insects. **Stomata** are very small openings in the epidermis of the leaf and stem that aid in the exchange of water vapor, carbon dioxide, and oxygen (Figure 7-4). Stomata are composed of two guard cells that can be open or closed depending on environmental factors and plant needs. Stomata are more numerous on the lower epidermis, or the underside of the leaf. The lower sides of corn and soybean leaves have more than 30,000 stomata per square inch (12,000 per square centimeter).

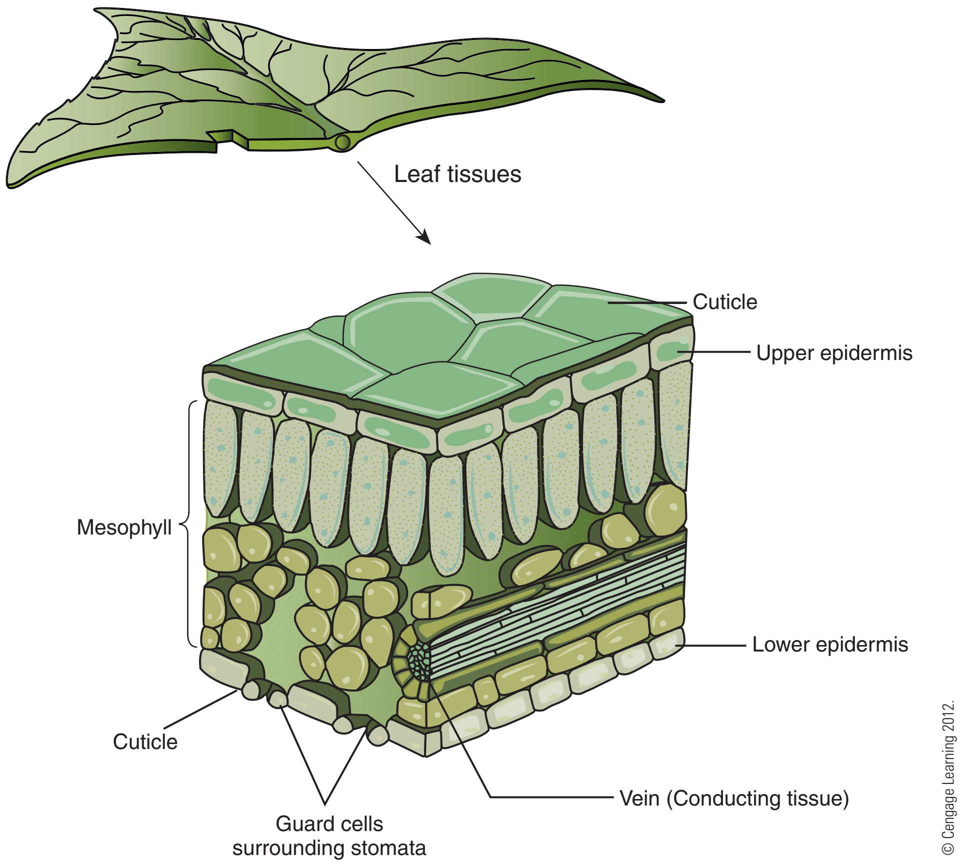


FIGURE 7-3
Cross section of a leaf that illustrates the epidermis and other leaf parts.

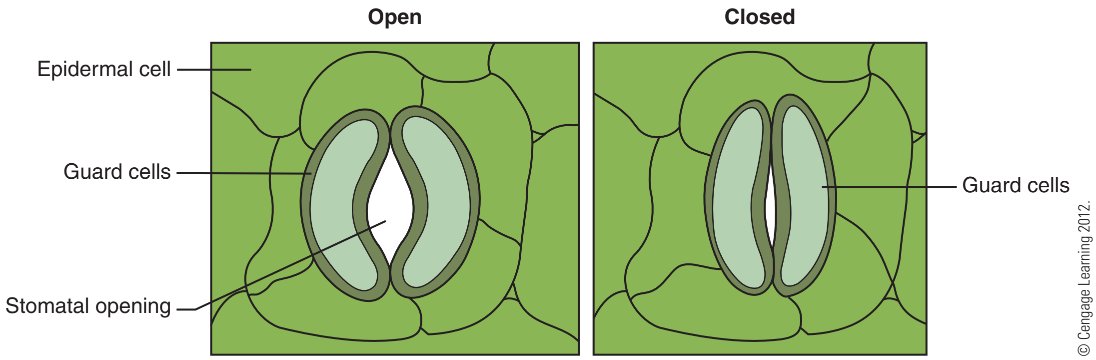


FIGURE 7-4
Diagram of stomata.

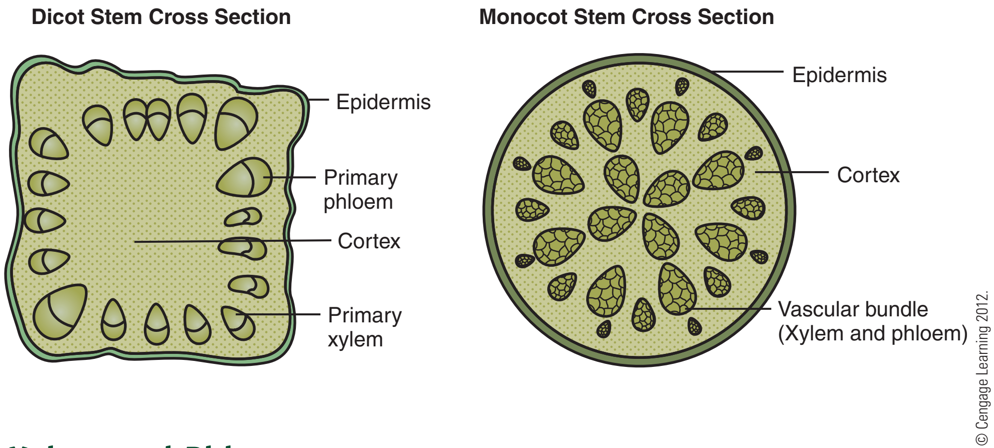


FIGURE 7-5
Cross section of a dicot stem versus a monocot stem.

Xylem and Phloem

Xylem and **phloem** make up the vascular bundles, or the conducting tissue, in the stems, leaves, and roots of plants. The xylem and phloem form a tunnel system throughout the plant for the movement of water and nutrients. The xylem transports water and minerals from the root system to the other plant parts. Xylem tissue also provides structural support for the plant as a result of secondary cell-wall formation and lignification (a process which makes the cell wall harder through the deposition of lignin). The phloem transports sucrose and other organic compounds throughout the plant. In a dicot plant stem, the vascular bundles are arranged in a ring that separates the cortex and pith (Figure 7-5). In monocot plants, the vascular bundles are scattered throughout the pith of the stem.

Ground Tissue

The **ground tissue** such as the pith and cortex is the tissue other than epidermal or vascular. It composes the bulk of the plant. It consists of **parenchyma**, **collenchyma**, and **sclerenchyma** cells. Of these three, the parenchyma cells are found in all plant organs. In leaves, parenchyma cells contain chlorophyll for photosynthesis. In stems and roots, they have potential to store energy. Collenchyma cells, found in the stem, and sclerenchyma cells have thickened cell walls and provide mostly structural support for the plant. These contain cellulose and lignin, which constitute the fiber described in Chapter 6.

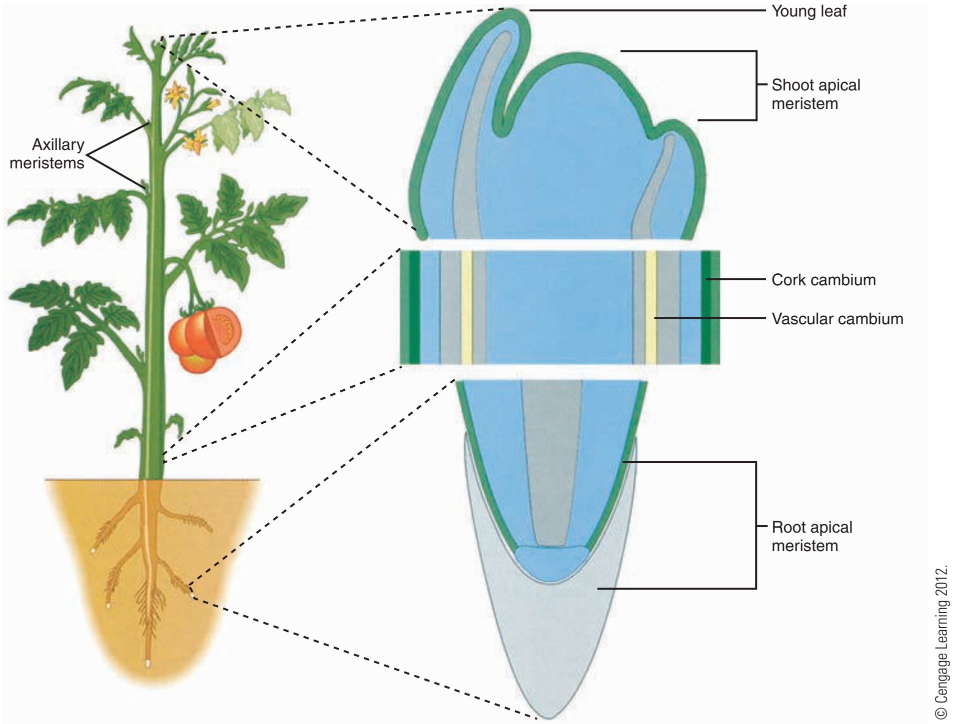


FIGURE 7-6
A tomato plant showing the locations of meristems. Dicots, like tomatoes, do not have intercalary meristems.

Meristems

Meristems are areas of actively dividing cells in plants. Meristems produce cells that can differentiate and form other tissue such as epidermis, and ultimately leaves and stems (Figure 7-6). There are several different types of meristems.

- **Apical meristems** are located at the tip or apex of a shoot or root. Primary growth usually occurs in the apical meristems. Apical dominance occurs when the apical meristem produces compounds that prevent the axillary meristems (see the discussion later in this section) from developing.
- **Intercalary meristems** are found in grasses and are independent from the apical meristems. They are responsible for the growth of the stem internodes and leaves. **Internodes** are the portions of the stem between the nodes. Intercalary meristems are located at the base of internodes, at the base of the leaf sheath, and at the base of the leaf.
- **Axillary meristems** are responsible for the development of buds for branches or flowers. They are located at the nodes where the leaves are attached to the stems. **Nodes** are enlarged portions of the stem to which leaves are attached and where vegetative and floral buds develop. In soybeans, axillary buds develop into flowers that, when fertilized, become pods containing seeds.
- **Secondary meristems** are responsible for lateral growth. There are two types of secondary meristems: cork cambium and vascular cambium. **Cork cambium** is often found in woody plant stems where it produces tissue that replaces the epidermis. **Vascular cambium** is found in the stems and roots of dicot plants and is a type of meristem that increases stem diameter. The effect of vascular cambium activity on stem diameter growth is most evident in the yearly rings that form in tree trunks.



Plant Hormones

Plant hormones are chemicals produced by plants that regulate growth and development. They are often produced in the meristems and can be transported to the parts of the plant where they are needed. Plant hormones can signal the differentiation of plant cells to develop into plant organs such as stems and leaves, or into specialized structures such as flowers and fruit. Some of the major classes of plant hormones and their effects are shown in Table 7-2.

Plant hormones can also be synthesized or isolated by people and used to manipulate crop-plant growth and development. In these instances, plant hormones are usually referred to as **plant growth regulators**. Plant growth regulators are used in many ways, particularly in horticultural crops. Examples include: auxins used to root cuttings of ornamental crops, gibberellins used to increase seed germination, and ethylene used to promote fruit ripening. They are also used to control weeds, such as auxins to control broadleaf weeds in a crop such as corn.

TABLE 7-2

Plant hormones, sites of synthesis, sites of action, and functions. *Adapted from Rost et al. (2006).*

Plant hormone	Synthesis site	Site of action	Function
Auxin	Developing seed embryos	Ovary	Fruit development
	Stem apex, young leaves	Expanding tissues	Cell elongation
		Roots	Lateral root initiation
		Axillary buds	Inhibits lateral growth (apical dominance)
Giberellins	Stem apex, young leaves	Stem internode	Cell division, cell elongation
	Embryo	Seed	Germination
Cytokinin	Root apex	Stem apex, axillary buds	Cell division (inhibits apical dominance)
Abscisic acid	Leaves	Guard cells	Stomata closing
	Ovule	Seed coat	Seed germination inhibition
Ethylene	Mature tissue	Fruit	Ripening

Plant Organs

A plant body has three vegetative organs: roots, stems, and leaves. Flowers are modified leaves containing the sexual reproductive organs necessary for seed production. Each plant organ has its own morphology and performs a specific function within the plant.

Roots

Roots serve several important functions for the plant. They anchor the shoot into the soil and support the upright growth of stems; they absorb minerals and water from the soil; and they provide storage of energy reserves. Storage of energy reserves is especially important in overwintering biennial and perennial plants such as sweetclover, carrot, sugarbeet, dandelion, and alfalfa. Some annual plants such as sweet potato have modified roots for extensive food storage.

Root Anatomy

The anatomy of the dicot and monocot roots is shown in Figure 7-7. Both monocots and dicots have xylem and phloem for conducting water and nutrients to the stem. In the dicot, the xylem cells are located in the center of the root in a star arrangement surrounded by the phloem. A layer of vascular cambium cells responsible for root diameter growth separates the phloem and xylem. A ring of endodermis and pericycle cells surrounds these vascular tissues. Branch roots arise in the pericycle and grow outward through the endodermis. The other major portion of the root is the cortex (made primarily of parenchyma tissue for energy storage) and the epidermis, or covering of the root. In the monocot root, alternating xylem and phloem cells encircle a central core of pith. A layer of cortex surrounds the vascular ring. Both monocots and dicots have numerous root hairs. They are extensions of the epidermis that significantly increase the root surface area.

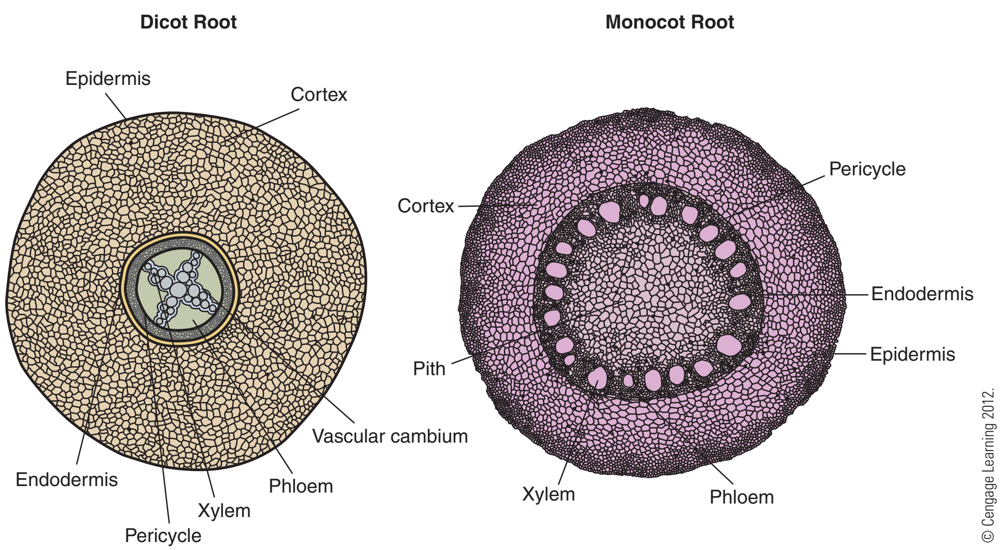


FIGURE 7-7 Cross section of dicot and monocot roots.

Root Morphology

Most plant species can be categorized as having either a **taproot** or **fibrous root system**, although many species may have a combination of both root system types (Figure 7-8). A taproot system usually consists of a large main root with small lateral roots. Alfalfa, carrots, and dandelions are examples of tap-rooted plants. A fibrous root system consists of several main roots that each branch and develop many lateral roots to form an interwoven mass. Grasses typically have highly branched fibrous root systems.

Root systems are most extensive in perennial plants and often have below-ground mass and length equal to the aboveground plant tissue. For most plant species, the greatest mass and length of the root system can be found in the top 1 foot (0.3 meter) of the soil. Some tap-rooted species such as alfalfa and trees have root systems with the potential to grow 30 feet (9 meters) into the soil.

Plants often have **adventitious roots** or roots that arise from atypical places such as nodes on stems. Examples of adventitious roots include brace roots that develop from the nodes on the base of a corn stalk (Figure 7-9) and roots that develop on the horizontal stems of white clover.

Rhizobia and Mycorrhizae

Many plants have beneficial associations with soil microorganisms. Plants in the legume family (e.g., soybean and alfalfa) form symbiotic (mutually beneficial) relationships with indigenous soil bacteria called *Rhizobia*. These bacteria invade

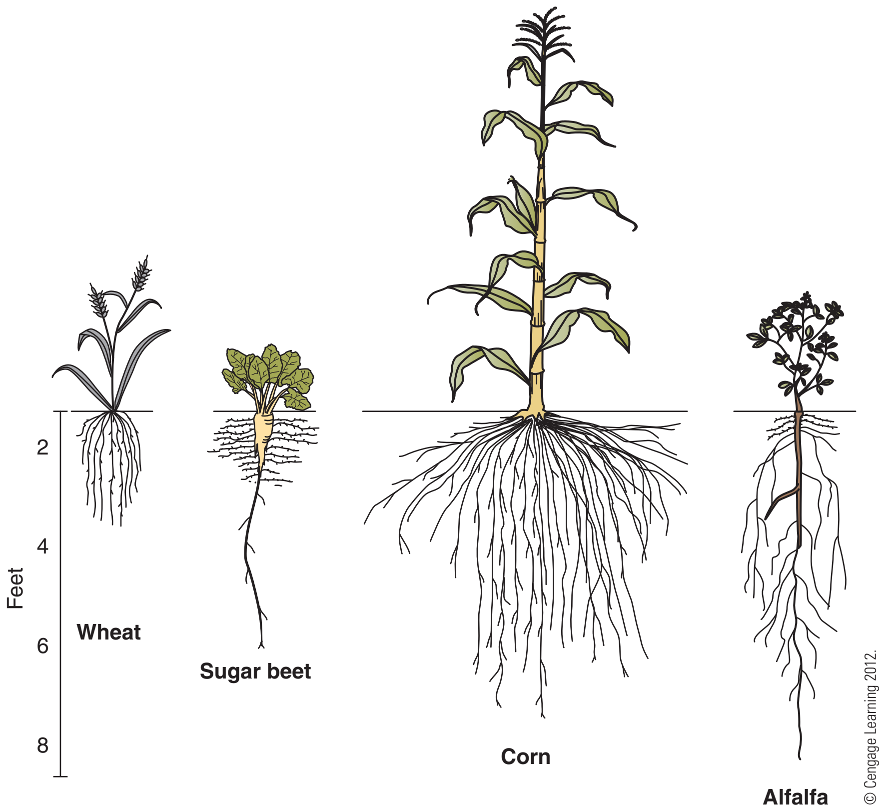


FIGURE 7-8
Root-system depths of monocot and dicot plants. Wheat and corn are examples of monocots and have fibrous root systems; sugar beet and alfalfa are dicots and have taproots.

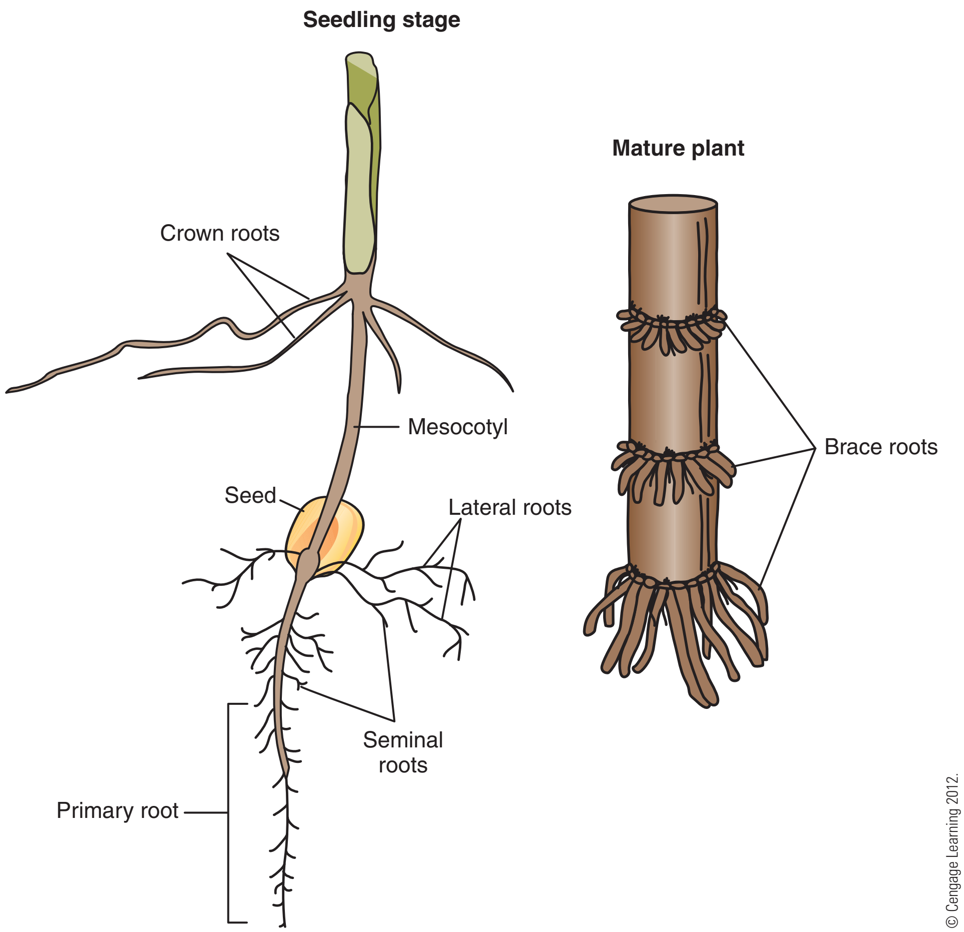


FIGURE 7-9
Various root types on a corn plant.

the plant's root hairs and form nodules that are connected to the vascular system of the plant. The bacteria receive energy and other nutrients from the plant and in return fix atmospheric nitrogen for the plant to use. The nature of this relationship is described in the next chapter. Many other plants form a symbiotic relationship with soil mycorrhizae or fungi. The fungi grow from the cortex of the plant root into the soil in threads. In exchange for energy from the plant, the fungus absorbs water and nutrients, especially phosphorous, which is immobile in the soil. Mycorrhizal fungi are critical for the growth of many native prairie grasses and legumes.

Stems

The **stem** is the primary supporting structure for the leaves, flowers, and fruits of a plant and is the conduit for the movement of water, nutrients, and products of photosynthesis between the crown of the plant and the roots. Stems can also conduct photosynthesis and store energy.

Stems can be distinguished from other plant parts by the presence of nodes and internodes. Any leaf, vegetative bud, or floral bud that arises from the node at the leaf axil is called an *axillary* bud, whereas the one that arises from the top is the *apical* bud. Stems are typically terminated by meristems that can produce additional vegetative or floral growth.

Grasses have **tillers**, or shoots (Figure 7-2), which arise from the crown and consist of stem and leaf parts and sometimes reproductive parts. These additional upright stems are common in perennial grasses, as well as small grains. Species with tillers include wheat, barley, and oats.

Most stems have a vertical structure, but some plants have modified stems that enable them to spread horizontally, reproduce asexually, and store energy (food) for survival (Figure 7-10). Examples of these modified stems include the following:

- **Rhizomes**, which are horizontal, underground stems that are important for asexual reproduction in plants. Plants with rhizomes include Kentucky bluegrass and Canada thistle.

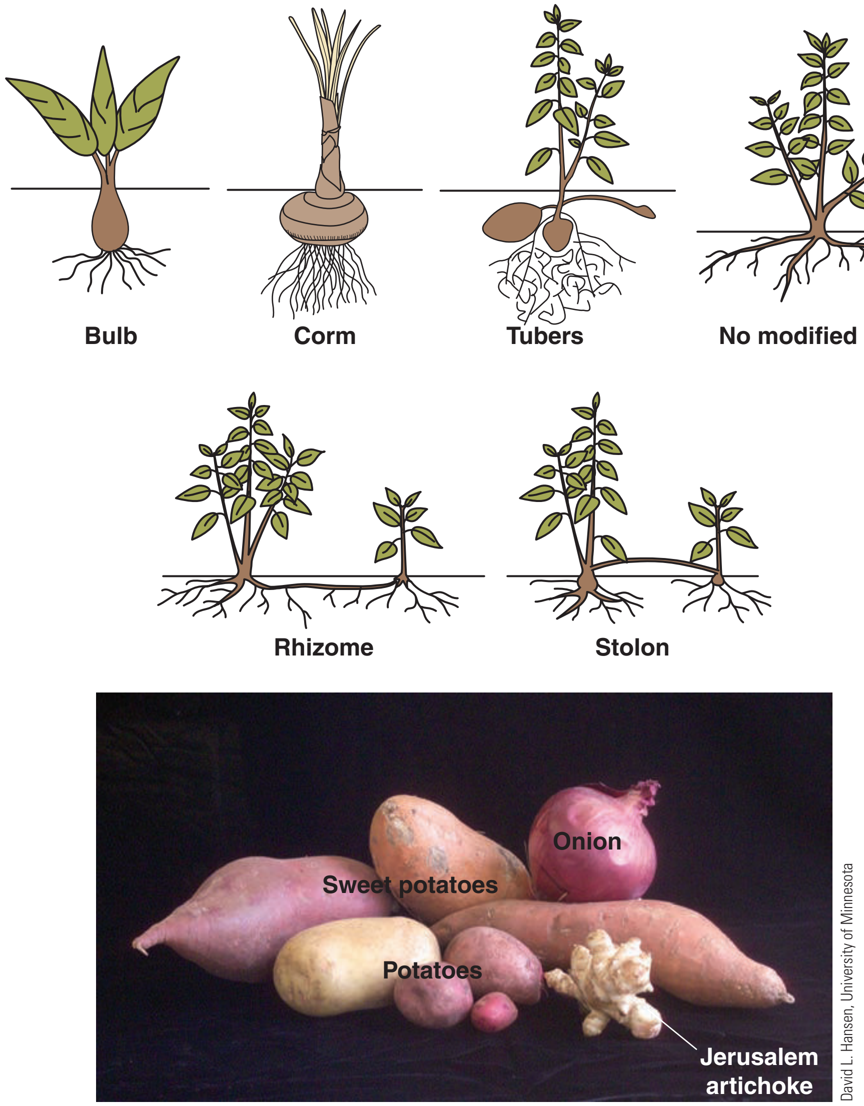


FIGURE 7-10 Examples of modified stems. Modified-stem crops include potato, onion, and Jerusalem artichoke. Also pictured for comparison are sweet potatoes, which are enlarged roots rather than modified stems.

- **Stolons**, which are horizontal, aboveground stems. These stems are also called *runners*. Plants with stolons include white clover, strawberry, and Bermuda grass.
- **Tubers**, which are enlarged, fleshy stems containing a significant amount of storage carbohydrates. The potato is a tuber, and the eyes of the potato are buds.
- **Bulbs**, which have a narrow stem surrounded by layers of concentric, fleshy rings. You can see these rings by cutting an onion or tulip bulb.
- **Corms**, which are compressed, solid, fleshy portions of an underground stem. Timothy and crocus have corms.

Growth Habit

Perennials can be characterized as **crown-formers** or **clone-formers** (Figure 7-11). Parent plants of crown-forming perennials often have deep tap roots and can survive for several years. Crown-formers depend on seed production for reproduction. Alfalfa and dandelion are examples of crown-forming perennials.

In clone-forming perennials, the original parent plants are replaced by new plants established asexually by rhizomes, stolons, or adventitious roots. Because of their "mobility," clone-formers can exploit new environments. Species that send out rhizomes are especially tolerant to climate extremes. Quackgrass, Jerusalem artichoke, and big bluestem are rhizome-forming plants. Bermuda grass and white clover are stolon-forming plants.

Another way to categorize plants by growth habit relates to the pattern in which a plant produces vegetative growth after flowering. Some plants are **determinate**, which means that once flowering initiates, the vegetative growth ceases. Fruit of a determinate plant will mature at about the same time. Examples

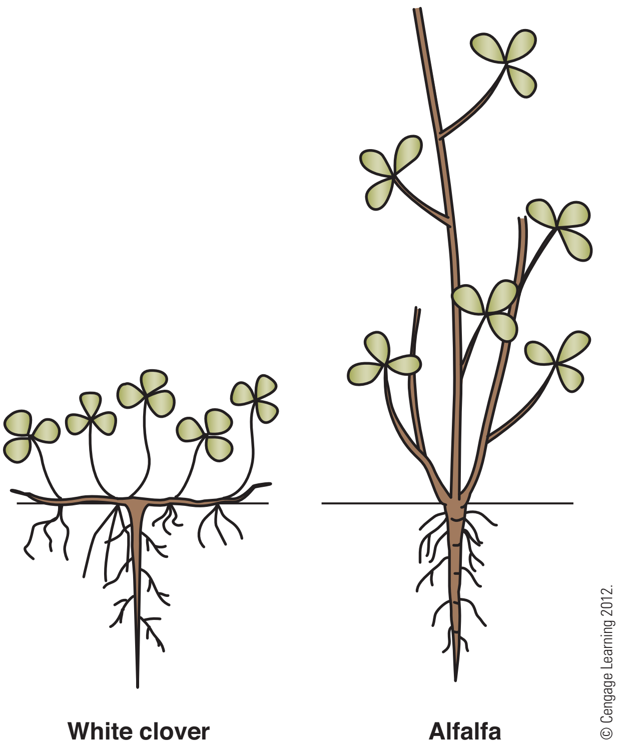


FIGURE 7-11
White clover is an example of a clone-former via its stolons, and alfalfa is a crown-former.

of determinate crops include corn and small grains. Plants that are **indeterminate** keep producing vegetation and new flowers after the first flowers are produced. The fruit of indeterminate plants will mature at varying times. Examples of indeterminate crops include potato and peanut. Some crops such as soybean and cotton can have both determinate and indeterminate varieties. The determinate or indeterminate nature of a crop greatly influences harvest method.

Leaves

Leaves are the primary organs where the essential processes of photosynthesis and transpiration occur. Light energy is captured in the chlorophyll of the leaf mesophyll cells, and gases such as carbon dioxide (CO_2), oxygen (O_2), and water (H_2O) are exchanged through stomata on the leaves. Stomata are composed of two guard cells whose turgor pressures open or close the pore opening. All leaves have veins, or **venation**, that are part of the vascular system of the plant for the movement of water and nutrients.

The leaves of monocot plants (grasses) consist of a **sheath**, **blade**, and **collar** (Figure 7-2). The blade is the flat surface of a leaf that is exposed for maximum interception of sunlight. The sheath is the lower portion of the leaf that surrounds the stem. The collar of a leaf, located at the union of the blade and sheath, has appendages such as auricles and ligules that can be used to distinguish species (Figure 7-12). Auricles are appendages that are attached to the collars of some grasses. They can be of various sizes and their tips can be rounded or pointed. Ligules are membranous structures that connect a blade to a sheath. Monocot leaves have parallel venation.

Dicot plants have either **simple** or **compound leaves** (Figure 7-13). Simple leaves are composed of a blade and a **petiole** that attaches the blade to the stem. Sugar beets and canola have simple leaves. Compound leaves have a blade made up of a number of leaflets that are attached to the petiole. These leaflets can have either a palmate, pinnate, or bipinnate (twice pinnate) arrangement. Soybeans have pinnately compound leaves. At the base of the petiole, some dicot species also have small attachments called stipules. Dicot leaves have netted venation.

Some plants have other modified leaves such as tendrils that help the plant to climb. In peas, pumpkin, and vetch, tendrils wrap around other plants or structures and provide support for the stem of the plant.

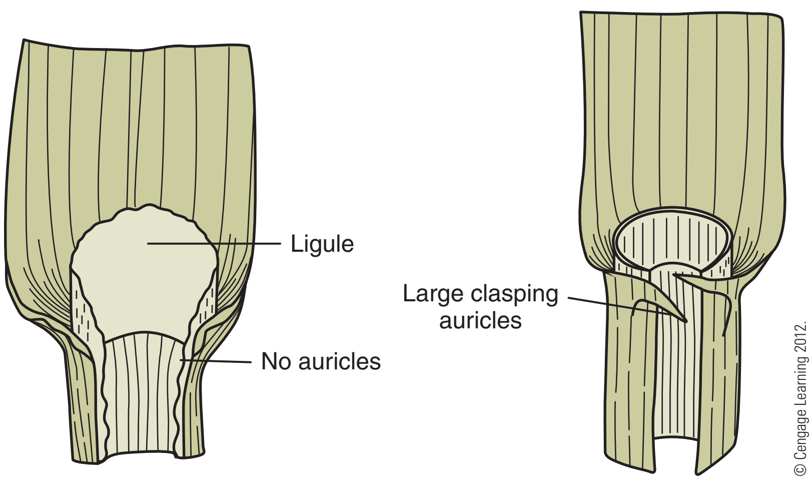


FIGURE 7-12
Grass collars of oats (left) and barley (right). This region is often used for identification purposes of the grasses.

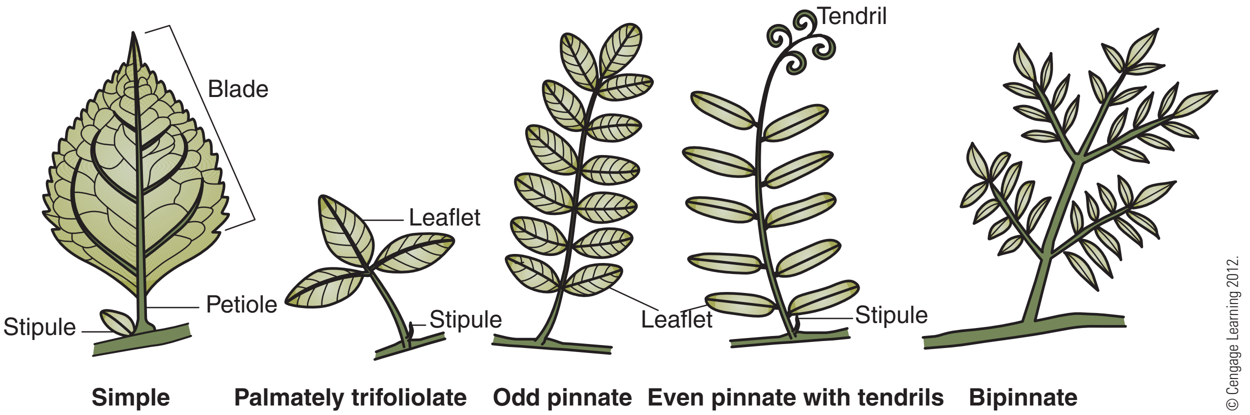


FIGURE 7-13 Examples of different types of dicot leaves. The first leaf is simple (or entire), whereas the others are compound. The compound leaves shown are all from legumes.

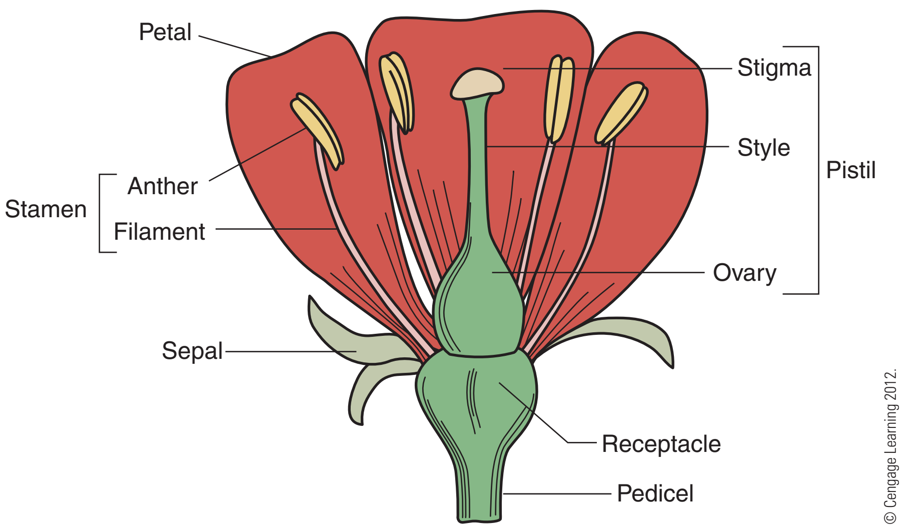


FIGURE 7-14
Parts of a flower.

Flowers

The process of sexual reproduction in plants begins in flowers. **Flowers** are modified leaves that may retain some leaf-like characteristics. Flower forms vary among plant families, but a general flower consists of four parts: **stamens**, **pistil**, **petals**, and **sepals** (Figure 7-14).

Stamens are the male component of the flower. Each stamen has a filament or stalk that supports the anther. The anther produces the pollen that contains sperm needed for sexual reproduction. Most flowers have several stamens.

The pistil is the female reproductive portion of the flower. The pistil is composed of the stigma, style, and ovary. During pollination, pollen attaches to the stigma and produces a pollen tube, which the sperm travels through in the style to the ovary. The ovary contains the ovules which contain an egg. Fertilization occurs when the male sperm and female ovules unite. These fertilized eggs within the ovary develop into seeds (Figure 7-15).

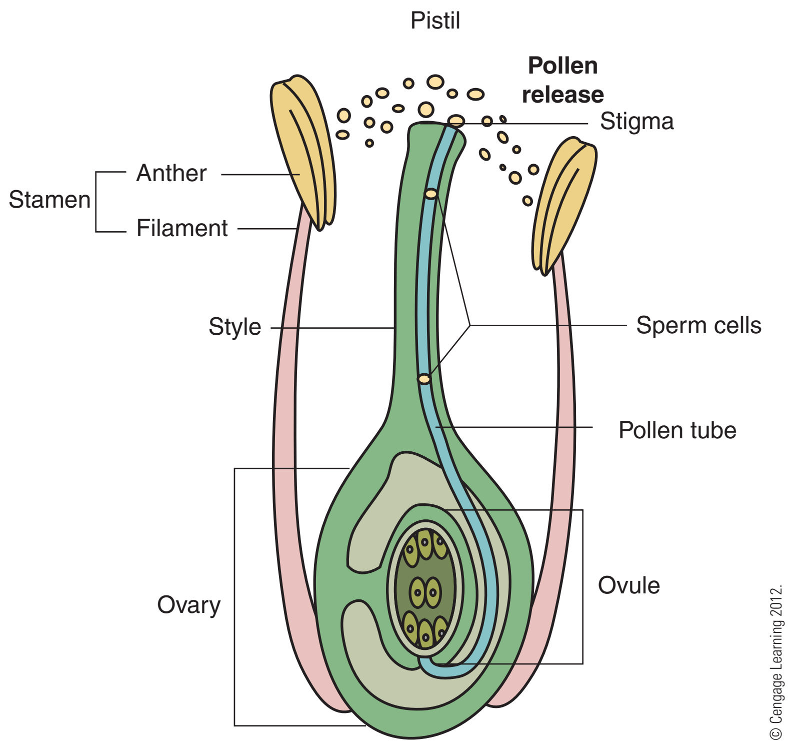


FIGURE 7-15
Pollination. The anther of the stamen releases pollen. A pollen tube is formed when the sperm attach to the stigma. The sperm travel down the style to the ovary. The sperm then unite with the eggs in the ovule to eventually form the seeds.

Petals are showy, modified leaves that are important for attracting pollinators. They also provide some protection to the immature stamens and pistils. Following fertilization, the petals often die. Located at the base of the petals, sepals are the green, leaf-like structures. In some plants such as cotton and alfalfa, the sepals are large and cover the entire flower bud before it opens. After these flowers open, the sepals become relatively small.

Classes of Flowers

Flowers can be categorized by whether all the flower parts are present (complete or incomplete) or by whether all the reproductive parts are present (perfect or imperfect).

Complete flowers are composed of stamens, pistils, petals, and sepals. Many plants that depend on cross-pollination (the movement of pollen from one plant to another) have complete flowers. Legumes are an example of plants that have complete flowers.

Incomplete flowers lack one or more of the four flower parts. Grass flowers lack both sepals and petals and instead have leaf-like coverings (lemmas and paleas) around the stamens and pistils, with glumes providing an additional covering (Figure 7-16). Awns are long appendages on the lemmas that are present in some species.

Perfect flowers have both stamens and pistils present. Soybean and alfalfa have perfect flowers.

Imperfect flowers are incomplete flowers that lack either the stamen or pistil. Corn and squash are examples of plants with imperfect flowers. There are two categories of plants with imperfect flowers: **monoecious** and **dioecious plants**.

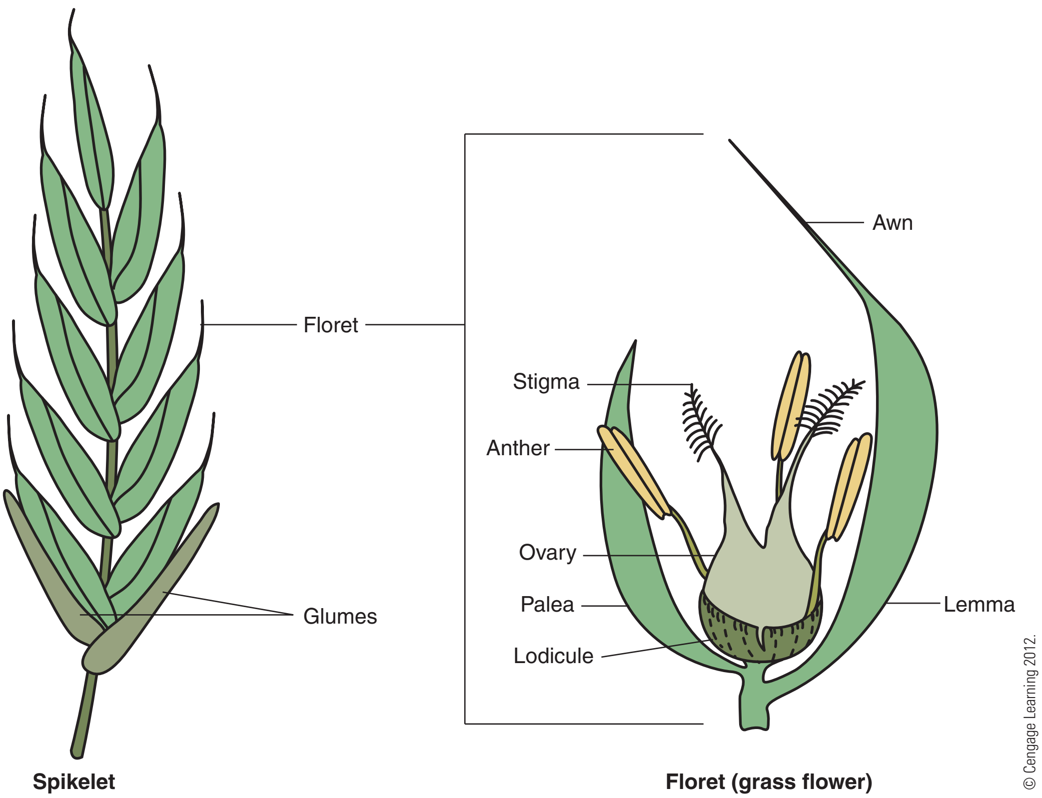


FIGURE 7-16 Parts of the grass flower. Grasses do not have petals or sepals, so their flowers are incomplete. Individual grass flowers tend to be inconspicuous.

- Monoecious plants have separate male and female flowers on the same plant. Corn is an example of a monoecious plant. The corn tassel is the male organ and is composed of only stamens, whereas the ear, or female organ, is composed of only pistillate flowers. Corn silks are elongated styles with a sticky stigma attached on the end.
- Dioecious plants have separate male and female plants. Therefore, if fertilization is to occur, both male and female plants must be present. Hops, hemp, and buffalo grass are examples of dioecious plants.

Inflorescences

Some crops such as cotton have flowers that occur singly, but many crops have flowers clustered together on branches or a system of branches. These arrangements of flowers are called **inflorescences**. In inflorescences, individual flowers (also called florets) are sometimes borne on a stalk called a pedicel (Figure 7-17). The flowers of legumes and grasses generally occur in inflorescences. There are several different types of inflorescences.

- The spike has flowers born directly on the main stalk of the inflorescence. Examples include wheat, rye, and barley.
- The panicle and raceme inflorescences have flowers in a branched pattern. Grasses such as oat and smooth brome have highly branched panicle inflorescences, whereas alfalfa has a raceme.

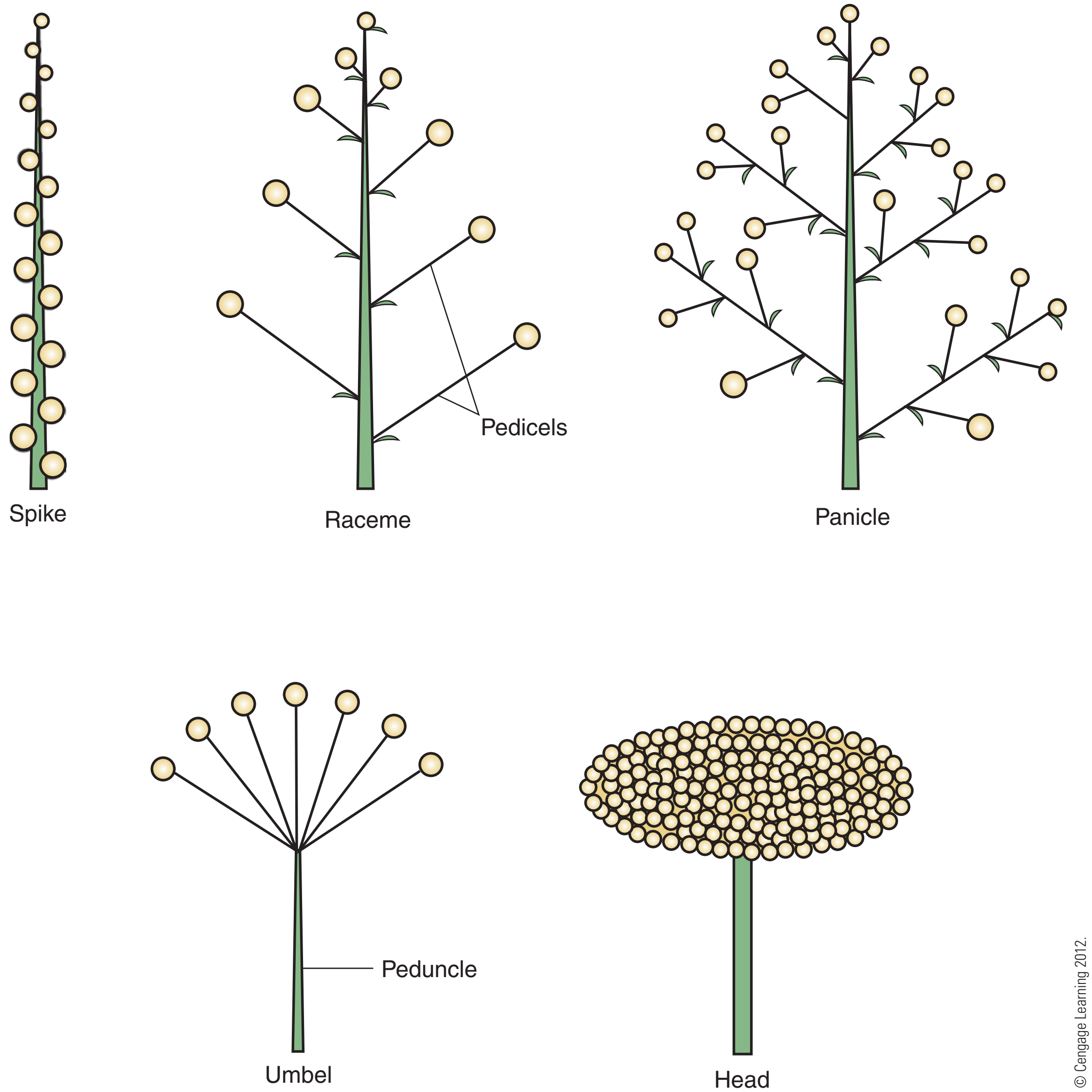


FIGURE 7-17 Various examples of inflorescences. Each circle represents an individual flower.

- The umbel is an inflorescence with all the flower pedicels originating from a single spot. Birdsfoot trefoil and carrot have umbel inflorescences.
- The head is an inflorescence with disk and ray flowers. Disk flowers are in the center of the head and develop into the seed, whereas ray flowers are colorful to attract insects. Examples of this type of inflorescence are sunflower and Canada thistle.

Fruits

The ovary of a plant is the enlarged, basal portion of the pistil. After fertilization, a ripened or mature ovary containing the seed or seeds is called a **fruit**. A fruit may be classified as either fleshy or dried. Fleshy fruits have a soft or "fleshy"

consistency and may be consumed by humans or other animals as food. This consumption of the fruit is important for dispersal of the seed. Examples of fleshy agronomic fruits include pumpkin and squash. Apple and tomato are fleshy fruits of horticultural significance.

Dry fruits are those that have hard seeds contained within the fruit wall. Dry fruits have either ovaries that split open at maturity and release their seeds (dehiscent) or ovaries that do not split open when mature (indehiscent). Examples of dehiscent fruits (generally called pods) include soybean, alfalfa, canola, and milkweed. All legumes have pods. Indehiscent fruits include sunflowers and grasses. The seed of grasses such as wheat and corn is actually a caryopsis, another type of fruit, that has the ovary wall (pericarp) attached to the seed.

Seeds

In plants, **seeds** are the mature, fertilized ovules within the ovary. Each seed contains an embryo (an immature plant) that has the genetic material essential for production of future generations of the species. Seeds also have food-storage reserves and are protected by a seed coat. The food-storage tissues of a seed are either cotyledons or endosperm. Seeds and plants are often described as monocots or dicots, the distinction being the number of cotyledons (seed leaves) they have (Figures 7-18 and 7-19). Monocots store their principal food reserves in the endosperm. Dicots store all their nutrients within their two cotyledons.

Seed Germination

Seeds are amazing structures that can remain viable for extended periods of time. **Germination** is the first step in the development of a plant from seed. To begin the process of germination, seed dormancy needs to be broken. Factors required to

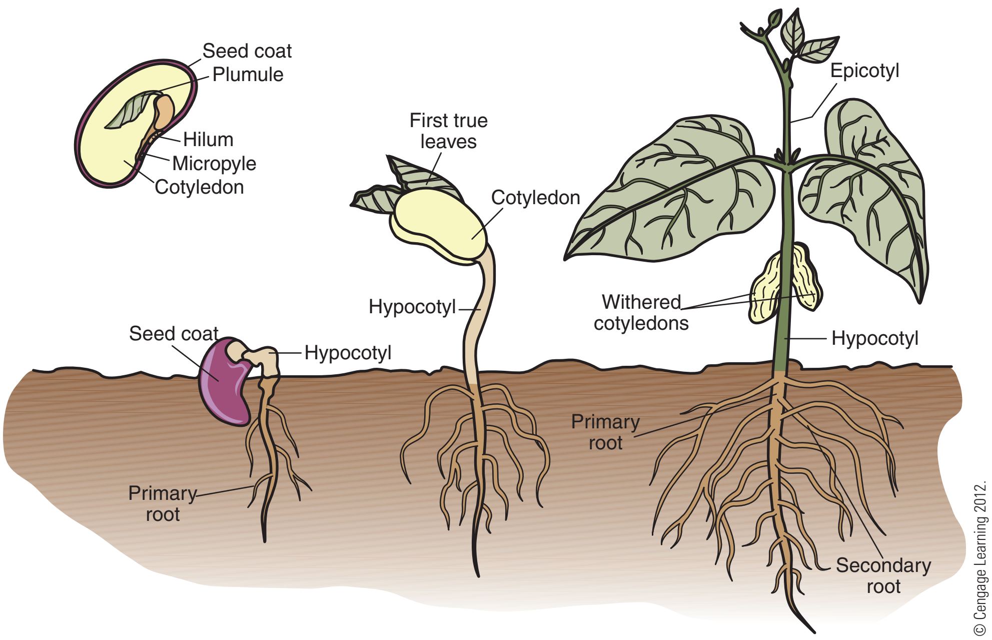


FIGURE 7-18 Epigeal germination (below). This example shows how a bean germinates. Above is a cross section of a bean seed. Beans are dicots.

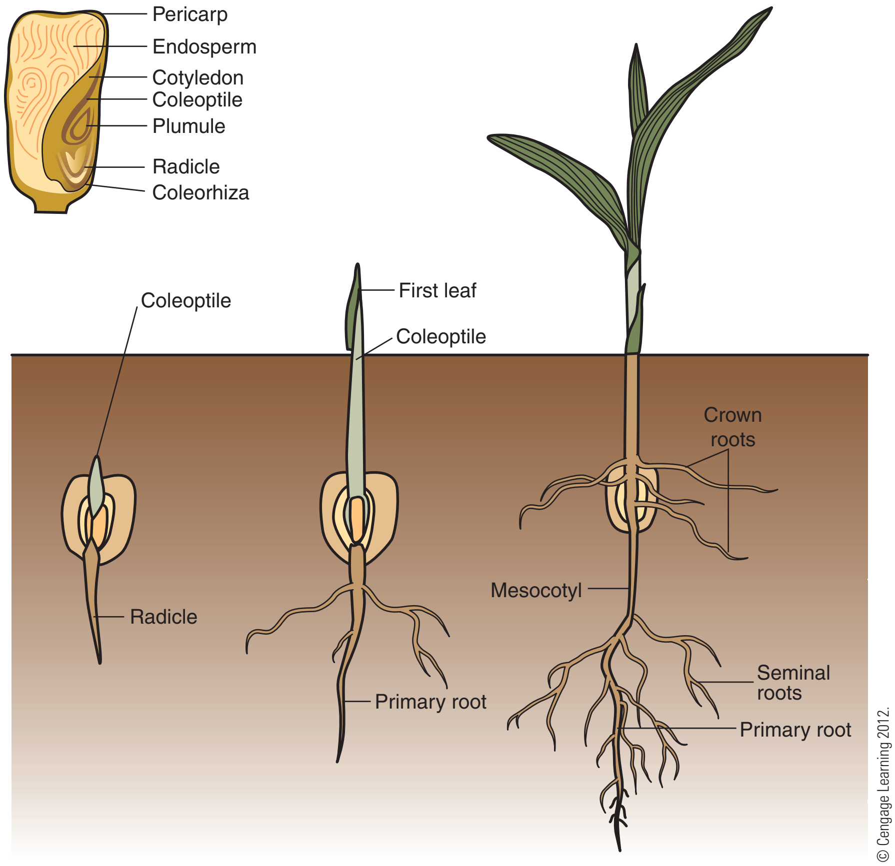


FIGURE 7-19
Hypogeal germination (below). This example shows how corn germinates. Above is a cross section of a corn seed. Corn is a monocot.

break dormancy include the correct environment (temperatures, moisture, light) and the decay of the seed coat by either natural or mechanical means. When these conditions have been met, germination begins.

The growth of the radicle (or embryonic root) is the first stage in germination. The radicle absorbs water and swells, causing the seed coat to split. The embryonic plant begins using its food reserves from either the cotyledons or endosperm to continue growing toward the soil surface.

There are two primary types of plant emergence from the soil: **epigeal** and **hypogeal**. In epigeal emergence, the hypocotyl, the portion of the embryonic plant between the radicle and the cotyledons, lengthens and carries the cotyledons above the soil surface. After the cotyledons emerge, the first true leaves of the plants develop, and the cotyledons begin to wither. The cotyledons develop chlorophyll and for a short time until true leaves develop, they conduct photosynthesis. Epigeal emergence is typical of dicots such as soybean and cotton (Figure 7-18). In hypogeal emergence, the cotyledons remain beneath the soil surface and the epicotyl emerges from the soil. Once the epicotyl breaks the soil surface, the first true leaves will develop and grow (Figure 7-19). This type of emergence is typical of grasses such as corn, wheat, and smooth bromegrass.

Review Questions

1. Describe two important differences between monocot and dicot plants.
2. What are the four basic types of plant tissues, and what are they composed of?
3. Define the term *meristematic tissue*. Describe the different types of meristems found in plants.
4. Describe the functional differences between the vascular tissues, xylem, and phloem.
5. What are the four organs that most plants have?
6. What are the main functions of roots? Name two types of root systems.
7. Describe the main functions of the stem.
8. Name and describe three types of specialized stems.
9. What are the main functions of leaves? Compare the major leaf parts of monocots and dicots.
10. What are the differences between complete and incomplete flowers?
11. What are the differences between perfect and imperfect flowers?
12. Explain the difference between monoecious and dioecious plants.
13. Describe three types of inflorescences.
14. How are seeds produced, and what parts do they contain?
15. What are the two types of germination? Describe each.

Critical Thinking

1. Knowing that corn is monoecious has implications for its successful propagation. Why else is it important to study plant anatomy and morphology as part of an agronomy course?

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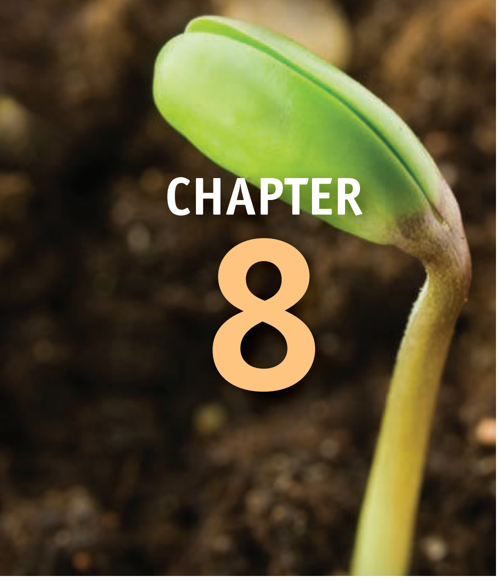
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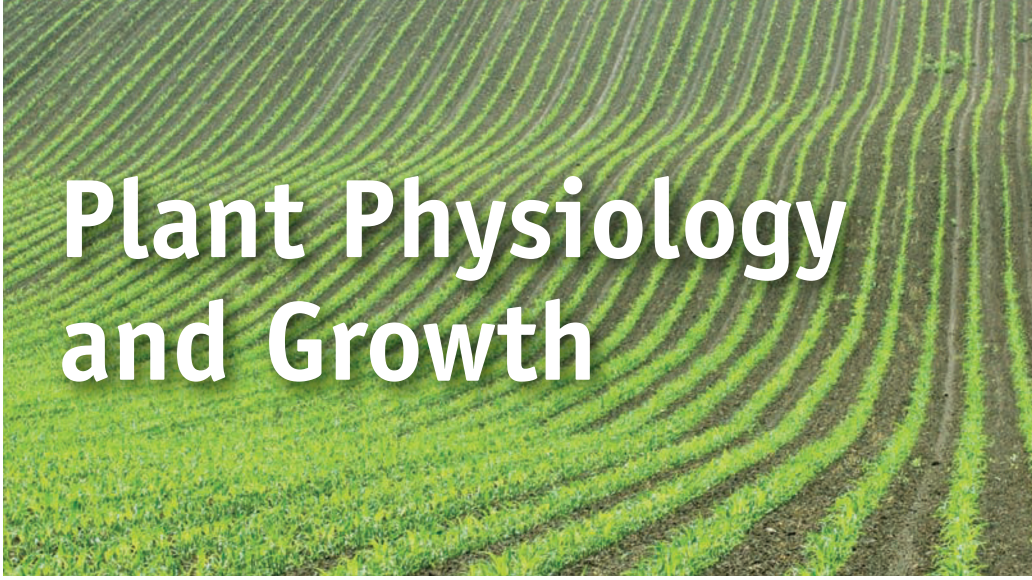
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CHAPTER 8

Plant Physiology and Growth







Key Concepts

- Metabolic energy transformations are critical for plants' survival and are the foundation for people's food sources.
- Photosynthesis is the process by which plants convert energy from sunlight to chemical energy.
- Respiration is the conversion of sugars and starches to energy for use in metabolism of living cells.
- Transpiration is the loss of water from stomata of plants. It has several important functions.
- Symbiotic nitrogen fixation is a process that makes atmospheric nitrogen available to plants of the legume family (*Fabaceae*).
- Photoperiodism is the reaction of plants to changing lengths of darkness. Reactions include flowering, dormancy, and leaf abscission.
- Vernalization is a photoperiod response during the winter that is important for triggering flowering in the spring.
- Plants are categorized as annual, biennial, or perennial based on their life cycle.
- The general developmental stages of annual plants include seed, seedling, vegetative, flowering, fruit, seed, and senescence.

Key Terms

adenosine triphosphate (ATP)
annual
biennial
C_3 plant
C_4 plant
Calvin cycle
CAM plant
carbon-fixation reaction
chloroplast
chlorophyll
day-neutral
development
dry matter
evapotranspiration (ET)
Feekes scale
Growing Degree Days (GDD)
growth
light reaction
long-day
mesophyll
metabolism
nicotinamide adenine dinucleotide phosphate (NADPH)
nodule
perennial
photoperiod
photoperiodism
photosynthesis
phytochrome
pseudo-annual
respiration
rhizobia
short-day
transpiration
vernalization

Introduction

The foods and fibers that we use from plants are the product of complex physiological and metabolic reactions that occur at a microscopic level within plant cells (Figure 8-1). What we cannot see, we often take for granted. **Metabolism** is the group of vital biochemical reactions that occurs in the cells of all living organisms including plants. Plant growth and development require many essential metabolic processes. Metabolic energy transformations are critical for plants' survival and are the foundation for the human food source. In this regard, the processes of photosynthesis and respiration require special consideration.

Another specialized metabolic reaction important to agriculture is biological nitrogen fixation. Biological nitrogen fixation is a symbiotic relationship between a legume and a soil bacterium that enables plants to use atmospheric nitrogen for growth. Because many crop plants contain from 80 to 95 percent water, this chapter also discusses the process of water movement in plants, as well as transpiration. Metabolic reactions fuel the growth and development of plants.

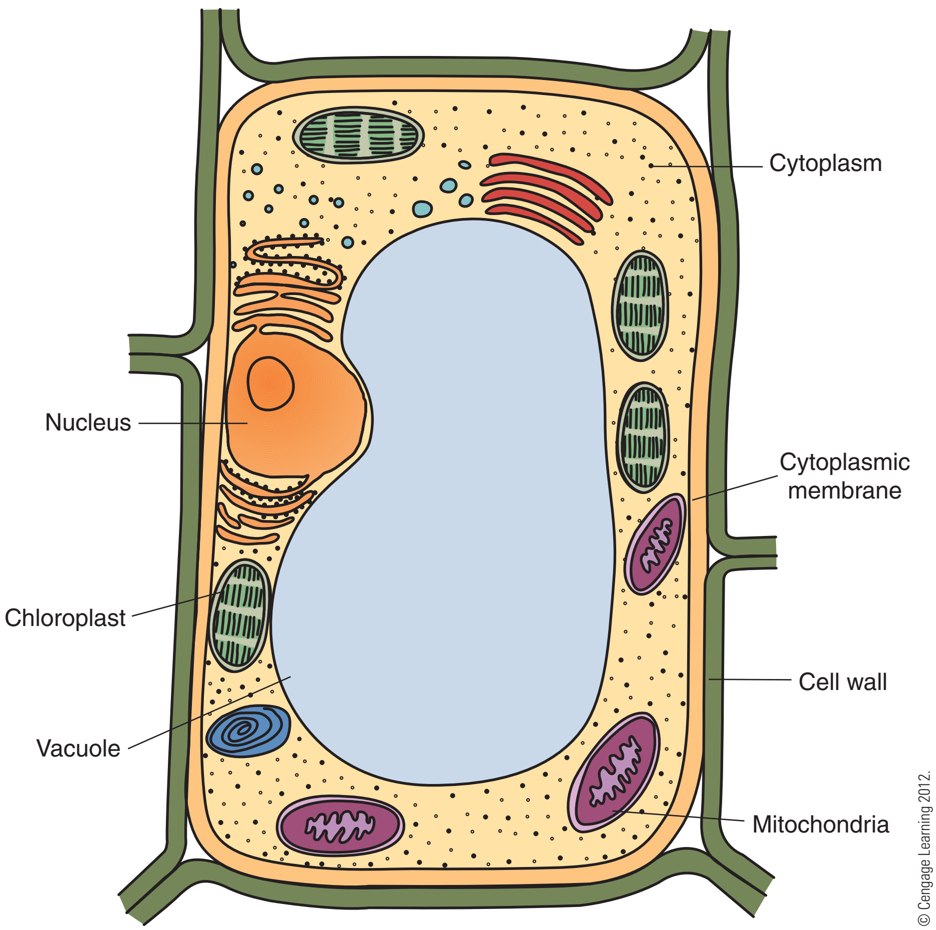


FIGURE 8-1 Diagram of a plant cell. The chloroplasts are the site of photosynthesis and the mitochondria are the site of respiration.

Photosynthesis

Whereas animals consume food derived from plants to acquire energy, plants use **photosynthesis** to acquire energy. Photosynthesis is the process by which plants convert energy from sunlight to chemical energy. Plants use this energy for all other metabolic processes. Photosynthesis from plants, directly or indirectly, is the fundamental source of food and energy for all other complex life on Earth. Photosynthesis performed by a plant during the growing season is directly related to its yield of food and fiber at harvest. The overall chemical reaction of photosynthesis is

$$6\ CO_2 + 12\ H_2O + \text{Sunlight} \longrightarrow C_6H_{12}O_6 + 6\ O_2 + 6\ H_2O$$

The final product is $C_6H_{12}O_6$ (glucose), a simple sugar that is used in metabolism and converted to other more complex compounds (see Chapter 6). Though this overall reaction seems simple, a number of intermediate steps occur.

Photosynthesis takes place in the **chloroplast**, an organelle located in the **mesophyll** cells of leaves (see Chapter 7). Chloroplasts are small, with as many as 200 per cell. Inside the chloroplasts are special molecules called pigments. These include the green **chlorophylls** *a* and *b* as well as yellow-orange carotenoids. These pigments absorb visible light in the range of 400–700 nanometers (Figure 8-2). The chlorophylls are most effective in absorbing the blue and red wavelengths of light and least effective in absorbing the green. The green portion of the spectrum is reflected, and this is why humans perceive plants as green. Chlorophyll converts the photons of light energy into chemical energy.

Light and Carbon-Fixation Reactions

Photosynthesis can be divided into two types of reactions: the light reactions and the carbon-fixation (or dark) reactions. The **light reactions**, or photochemical reactions, are the first part of photosynthesis and the only ones actually requiring light. In this step, the photons of light energy strike the chlorophyll in chloroplasts and set off a chain of reactions caused by electron transfers. Water is split into

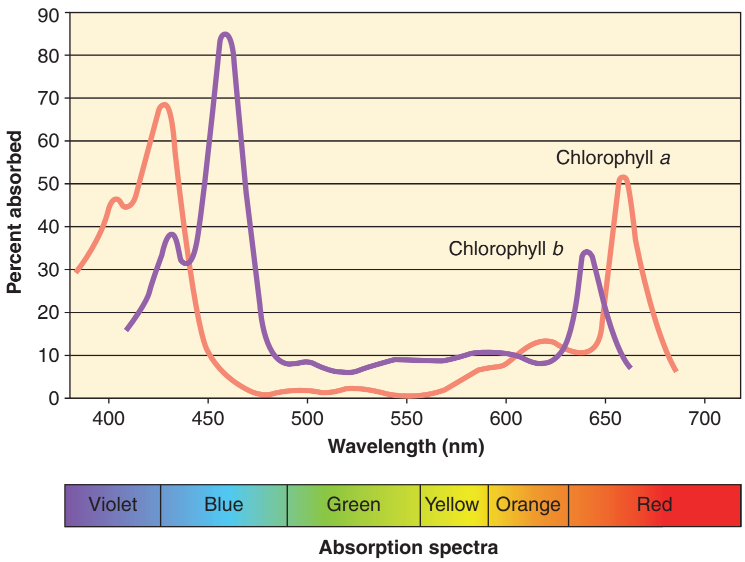


FIGURE 8-2
The absorption spectra for chlorophylls *a* and *b*. Note the peaks in the blue and red parts of the light spectrum.

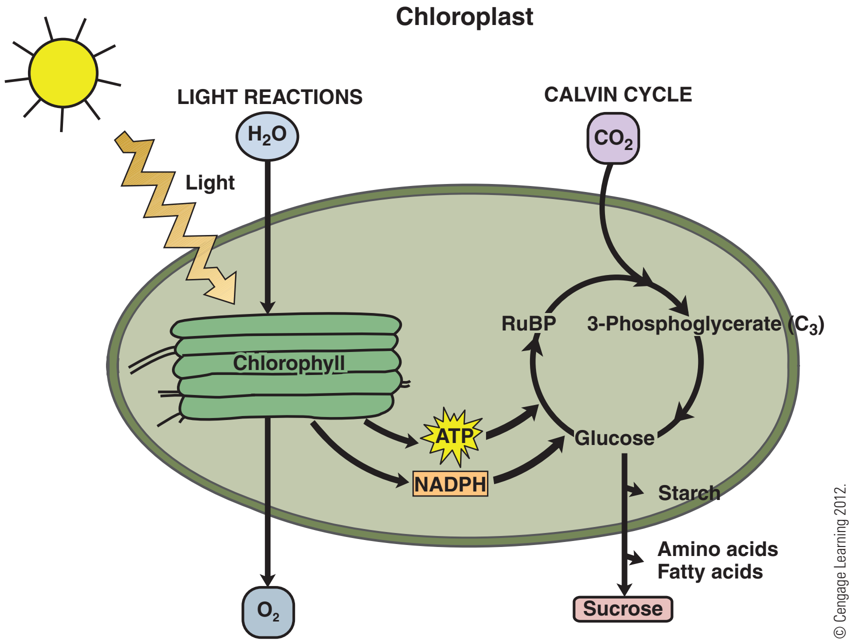


FIGURE 8-3
An overview of the light and carbon-fixation reactions. Photosynthesis consists of light reactions that produce ATP and NADPH, which are used in the carbon-fixation reactions (Calvin cycle).

hydrogen and oxygen, and two energy compounds—**adenosine triphosphate (ATP)** and **nicotinamide adenine dinucleotide phosphate (NADPH)**—are produced. This energy is used in subsequent reactions.

The second part of the photosynthetic process is the **carbon-fixation reactions**, or dark reactions. For these reactions to occur, CO_2 in the air diffuses through open stomata into the chloroplast within the mesophyll cells of the leaf. Then, NADPH and ATP made in the light reaction power the reduction of CO_2 to simple sugars. The collective process that involves many intermediary compounds is called the **Calvin cycle**, or C_3 cycle. As shown in Figure 8-3, CO_2 is added to a five-carbon compound called ribulose diphosphate (RuBP). The resulting six-carbon compound is then split into two three-carbon molecules (phosphoglycerate, PGA). This cycle is called the C_3 cycle because 3-PGA is the first stable compound. PGA is converted to glucose, which is used in metabolism and converted to disaccharides or polysaccharides for transport or storage. Plants that use the C_3 cycle are called **C_3 plants**.

The majority of the world's plants originating in temperate regions of the world (e.g., alfalfa, wheat, soybean, smooth bromegrass) and a few subtropical species (e.g., cotton, tobacco, peanut) are C_3 plants. Photosynthesis in C_3 plants is most effective at temperatures from 10–25°C and decreases thereafter. C_3 photosynthesis is inefficient in warm, high-tropical climates, and when CO_2 levels in the leaf are low such as occurs during drought when stomata are partially closed. This is because C_3 species have a version of respiration called *photorespiration* that can use up a significant portion of the carbon energy fixed during photosynthesis.

Variations in Carbon Fixation: C_4 and CAM

Plants adapted to tropical environments of high air temperature, drought, and high light intensity have alternative systems of carbon fixation. **C_4 plants** have a different leaf anatomy and an enzymatic system that first fixes CO_2 into a

TABLE 8-1

Major differences between C_3 and C_4 plants. *Adapted from Salisbury and Ross (1992)*.

Characteristics	C_3 plants	C_4 plants
Leaf anatomy	No distinct bundle sheath of photosynthetic cells	Well-organized bundle sheath, rich in chloroplasts
Carboxylating enzyme	Rubisco	Phosphoenolpyruvate (PEP) carboxylase, followed by Rubisco
Transpiration ratio (kg H_2O per kg dry matter produced)	450–950	250–350
Photorespiration	Yes	No
Optimum temperature for photosynthesis	59–77°F (15–25°C)	86–117°F (30–47°C)
Minimum ppm CO_2 required for photosynthesis	30–70	0–10

three-carbon compound (phosphoenol pyruvate; Table 8-1). The first compounds formed are the four-carbon compounds malate and aspartate (Figure 8-4). These compounds are then transferred to bundle sheath cells that surround the vascular system. In these cells, CO_2 is released to the Calvin cycle that then generates glucose and other sugars. Only about 10 percent of plant species are C_4 plants, but some are very significant for world agriculture. Examples of C_4 plants include corn, sorghum, amaranths, and millet. Many prairie grasses also have the C_4 cycle including big bluestem, Indiangrass, and switchgrass.

Crassulacean acid metabolism (CAM) plants have yet another type of carbon fixation. **CAM plants**, like C_4 plants, are adapted to hot temperatures. They use the C_3 and C_4 pathways like C_4 plants, but they use the C_4 pathway at night and the C_3 pathway in the day. This enables these plants to preserve water because they open their stomata only at night. Examples of CAM plants include cacti and pineapple. About 3–4 percent of plant species are CAM plants, but the most significant types of plants for crop production are C_3 and C_4 plants.

Respiration

The conversion of sugars formed through photosynthesis to energy (ATP) for use in metabolism of living cells is called **respiration**. Plants use this energy for cell maintenance, growth, and building new tissues. One molecule of glucose formed

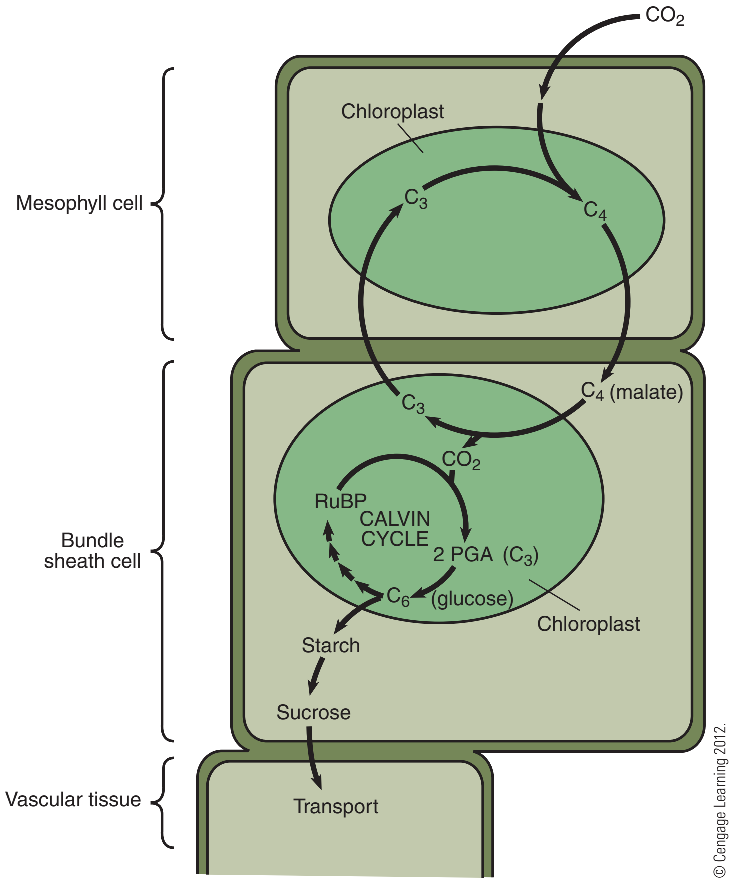


FIGURE 8-4
The C_4 pathway is found in tropical species such as corn. In contrast to the C_3 pathway, it involves an intermediate step in carbon fixation before the Calvin cycle.

during photosynthesis results in the production of 36 ATP molecules. The overall process of respiration occurs in both the cytoplasm and the mitochondria—small, microscopic organelles within the cytoplasm of living plant cells. The overall reaction that occurs in respiration is

$$C_6H_{12}O_6 + 6\ O_2 \longrightarrow 6\ CO_2 + 6\ H_2O + \text{Energy (ATP and heat)}$$

Respiration, like photosynthesis, is a complex process with many steps. In summary, glucose and oxygen are transformed into carbon dioxide, water, and energy. The four primary processes of respiration include the following:

1. Glycolysis, which occurs in the cell's cytoplasm. Glucose is split into two three-carbon molecules (i.e., pyruvate). This reaction also produces ATP, NADH, and water. ATP and NADH are both high-energy compounds.
2. Pyruvate enters the mitochondria and is split into CO_2 and acetyl coenzyme A (acetyl CoA). This reaction also produces NADH.
3. The Krebs cycle uses acetyl CoA to produce ATP and NADH, and it releases CO_2 and water. The NADH will be used in the next step to generate more ATP.
4. Oxidative phosphorylation is the final step of energy formation and occurs within the mitochondrial membrane. NADH is used to synthesize additional ATP.

For an overview of how photosynthesis and respiration are related, see Figure 8-5. A comparison of photosynthesis and respiration is shown in Table 8-2.

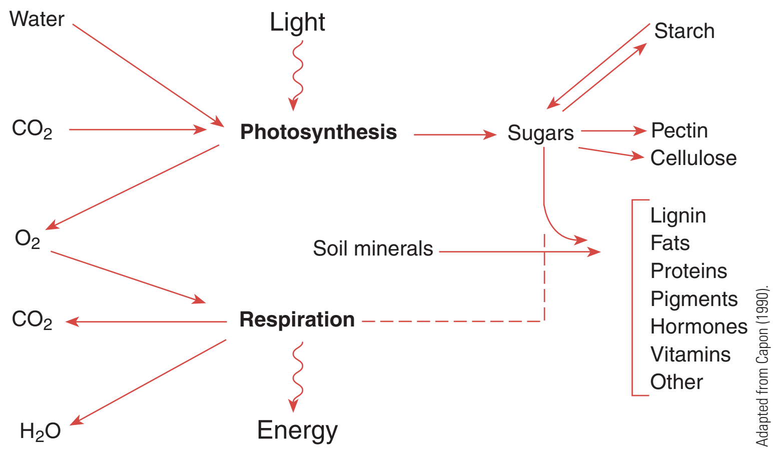


FIGURE 8-5
Plant metabolism—photosynthesis and respiration.

TABLE 8-2

A comparison of photosynthesis and respiration.

Photosynthesis	Respiration
Occurs in light	Occurs in dark and light
Produces sugars	Uses sugars
Stores energy	Releases energy
Uses H_2O	Produces H_2O
Uses CO_2	Produces CO_2
Releases O_2	Uses O_2

Transpiration

Transpiration is the process of water loss from the stomata of plants. Plants vary in their transpiration rates. Individual crop plants such as corn and sunflower can transpire from 0.5 gallon to more than 1 gallon (2 to 5 liters) per day. Large trees can transpire more than 50 gallons (200 liters) per day. Transpiration has several important functions including cooling of the plant, movement of nutrients within the plant, and uptake of mineral nutrients. Transpiration is driven by the sun's energy and a moisture-concentration gradient. Water moves along a gradient from the roots, where there is the most water (or a high concentration) to the leaves, where there is the least water (or a low concentration). Transpirational pull creates suction that pulls available water from the soil.

Root hairs that develop behind the meristematic region of a root tip (see Chapter 7) absorb water from the soil. Water molecules and any dissolved minerals pass through the epidermal cell membrane of the root hair. As it moves from the epidermal cells to the xylem, water passes through the root cortex, endodermis, and pericycle.

Water travels through the xylem tissue to the veins of the leaves and finally into the mesophyll (Figure 8-6). The plant will close its stomata and wilt if the available soil moisture is inadequate to support transpiration. Transpiration is

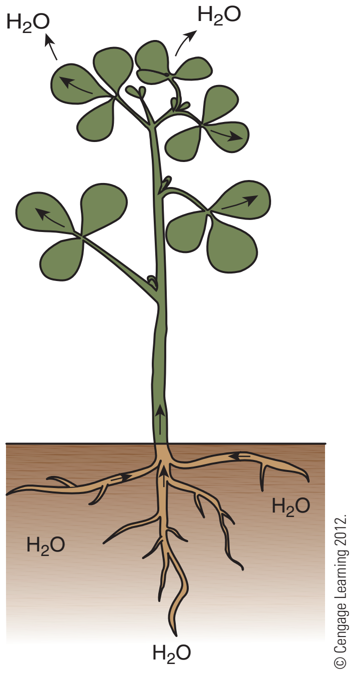


FIGURE 8-6
Water moves upward through the vascular system in the plant and out the stomata, like water pulled up through a straw. The water deficit in the leaves is provided by the air.

affected by soil moisture content, high air temperatures, low water concentration in the air, and air movement. Therefore, on hot, dry, windy days with low relative humidity, we can expect plants to use more water. Factors that affect transpiration include the following:

- The number of stomata a plant has and their size can influence transpiration.
- The process of transpiration is dependent on the presence of soil moisture. Therefore, climate and local weather that provide water and agronomic factors (e.g., weed control, crop residues, or fallowing) that minimize water loss enhance transpiration.
- Water evaporation within the leaf and transpiration are nearly doubled for every 10° rise in air temperatures within an air temperature range of 50–86°F (10–30°C).
- Air-moisture content (or humidity) influences water loss because water molecule change from liquid to gas is dependent on the concentration of water molecules in the air. A greater concentration of water molecules in the air suppresses the escape of additional water molecules to the air.
- Wind or air movement pulls water vapor away from the leaf surface and increases the transpiration pull.

Transpiration facilitates the absorption of many essential minerals that are soluble in water. Minerals are moved throughout the plant within the water stream.

Evapotranspiration

Evapotranspiration (ET) is the plant's total water use. As the name suggests, ET includes the actual water loss in transpiration as well as water that is evaporated from the surface of the leaves or from the soil surrounding the plant. A plant's total water use varies greatly. The ET ratio (weight of water required to produce the weight of the crop's dry matter) depends on several factors including type of

photosynthesis (e.g., C_3 or C_4) and various adaptations (e.g., number of stomata, presence of hairs on leaves). C_4 plants are the most efficient, requiring the least water to produce a kilogram of dry matter. C_3 legumes are the least efficient. For example, alfalfa requires 858 kilograms (1892 pounds) of water to produce 1 kilogram (2.2 pounds) of dry matter, whereas proso millet requires only 267 kilograms (589 pounds) of water. Crops' evapotranspiration rates can be used in irrigation scheduling—see Table 8-3 for approximate seasonal ET amounts for different crops.

TABLE 8-3

Typical ET values for crops in the Midwest over one year. *Adapted from Parker (2004)*.

	Yearly ET	
Crop	**Inches**	**Centimeters**
Alfalfa	31–36	79–91
Sugar beets	24–26	61–66
Corn	23–28	58–71
Soybeans	20–25	51–64
Sorghum	18–23	46–58
Winter wheat	16–18	41–46
Dry beans	15–16	38–41



How Plants Control Water Loss

Plants control water loss by regulating the opening and closing of the stomata. *Stomata* is derived from the Greek term *stoma*, which means mouth. Stomata are very small openings (typically less than 40 micrometers long) in the plant epidermis that regulate exchange of water vapor, carbon dioxide, and oxygen. Leaves of crops can have as many as 125,000 stomata per square inch (50,000 per square centimeter). Stomata are also on the stems of plants. They consist of pores surrounded by a pair of guard cells that regulate the opening and closing of the pore by changing shape in response to an increase in water pressure, or turgidity (see Chapter 7). Fully turgid cells bow apart and open the pore. When deflated, the guard cells close the pore. Guard cell water content is regulated by potassium content. Potassium accumulation in guard cells causes water accumulation and opens the pore. Stomata of most plants close during water deficits to prevent water loss and at night when photosynthesis is not occurring.

Plants adapted to hot and dry environments have other specific morphological adaptations that affect transpiration.

- Stomata are located primarily on the underside of the leaf, where they are protected from direct exposure to sunlight. Lower underside leaf temperatures lead to less transpiration. For example, corn has about 5000 stomata per square centimeter on the upper leaf surface but more than 10,000 on the lower leaf surface.

- Leaf surfaces are covered with short hairs (called pubescence) that shade the stomata and reduce leaf temperature as well as reduce water vapor loss from the leaf surface. Corn and sunflower have considerable leaf and stem pubescence.
- Leaf surfaces are covered with a thick, waxy coating (the cuticle) that decreases water movement directly from epidermal cells. Sorghum, a crop especially adapted to low moisture regions, has a whitish, waxy coating (called glaucous) on stems and leaves.
- Stomata are sunken on the leaf surface. This protects the stomata from wind.
- Leaf curling occurs during moisture stress, when leaves can fold and roll to decrease surface area and reduce stomata exposure to sun and air. The rolling of corn leaves is a typical symptom of moisture stress.

Symbiotic Nitrogen Fixation

Nitrogen is one of the most important elements for plants and is the most limiting nutrient in terrestrial environments. Much of the world's nitrogen is in the atmosphere, where it is the most abundant gas (see Chapter 10). Symbiotic nitrogen fixation is a process that makes atmospheric nitrogen available to some plants. Plants from the legume family (*Fabaceae*) commonly engage in symbiotic nitrogen fixation. However, some nonlegume species (mostly trees and shrubs) and free-living algae are also able to conduct biological fixation. This mutually beneficial (symbiotic) partnership occurs between legumes and bacteria collectively known as **rhizobia**. The legume plant supplies nutrients and energy to the bacteria that reside in root nodules. A bacterial enzyme, nitrogenase, converts nitrogen from the soil into ammonia (NH_3), which is reduced to ammonium (NH_4) that is used by the legume plant to form amino acids and protein. This process is costly for the plant, and if nitrogen levels in the soil are high, plants may reduce N_2 fixation levels. The overall reaction that involves the nitrogenase bacterial enzyme is

$$N_2 + 8H^+ + 16\ ATP\ (energy) \longrightarrow 2NH_3 + H_2 + 16ADP$$

Rhizobia that are present in the soil, or supplied in inocula to the seed, infect plant root hairs and stimulate development of tumor-like **nodules** on the roots. A specific rhizobial species is required for a given legume species. For example, bacteria infecting and nodulating white clover will not effectively nodulate soybean. The amount of fixed nitrogen varies depending on the symbiosis (Table 8-4). Some of the fixed nitrogen can be transferred to nonfixing plants grown in mixtures or may be used by subsequent crops in crop rotations.

Nodule Formation

The following is the process of nodule formation, as shown in Figure 8-7:

1. Root hairs grow. They release root exudates (flavonoids, sugars, amino acids, and so on), which attract specific rhizobia to the root.

TABLE 8-4

Quantities of nitrogen fixed by various legumes. Legumes vary in the amount of atmospheric nitrogen they can fix. This variation is in part due to the relative effectiveness of the symbiosis between plants and the bacteria. *Sheaffer et al. (2003).*

	Nitrogen fixed per year	
Legume	**Pounds/acre**	**Kilograms/hectare**
Alfalfa	70–200	78–224
Birdsfoot trefoil	44–150	49–168
Crownvetch	98	110
Cicer milkvetch	140	157
Crimson clover	57	64
Hairy vetch	99	111
Kura clover	17–158	19–177
Lentil	149–168	167–188
Red clover	60–200	67–224
Soybean	20–200	22–224
Sub clover	52–163	58–183
Sweet clover	120	135
White clover	115–180	129–202

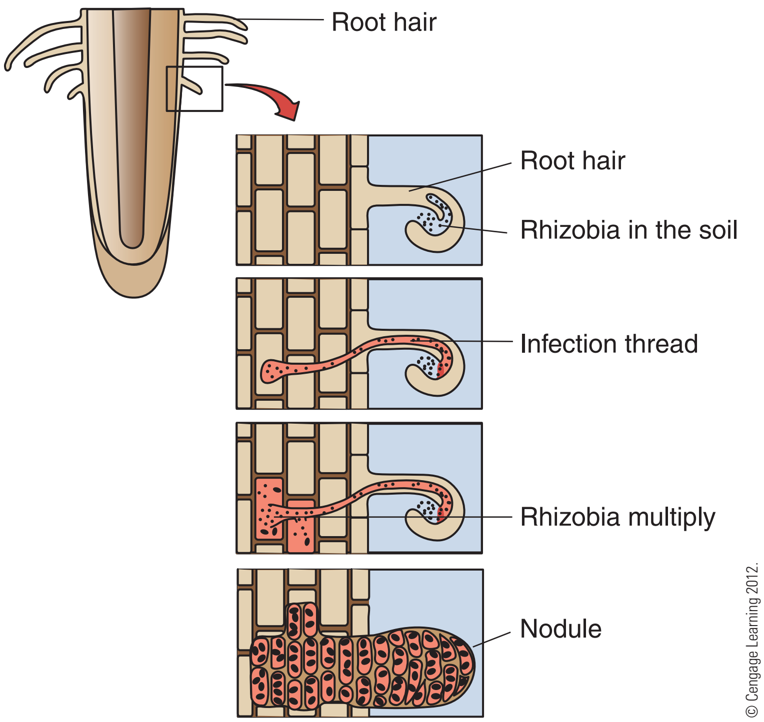


FIGURE 8-7
The nodulation process. Specific bacteria from the soil enter a legume's root hairs and ultimately cause a proliferation of root cells forming a nodule. Within the root, the bacteria multiply and are converted to bacteroids.



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FIGURE 8-8
Nodules on birdsfoot trefoil and red clover. Note the round nodules on birdsfoot and the elongated (or lobed) ones on red clover. Round nodules are annual, and elongated nodules are perennial.

2. The rhizobia attach to the root hair surface.
3. The root hair curls, entrapping the rhizobia.
4. The rhizobia digest the cell wall and form an infection thread into the center of the root. Within the thread, the bacteria divide and increase in number.
5. The rhizobia induce division of the root cells.
6. A nodule is formed from the protrusion of the root cells to the surface of the root.
7. Within the individual root cells, the bacteria become devoid of a cell wall and become bacteroids, which develop the nitrogenase enzyme and fix atmospheric nitrogen.

Nodule shapes vary and can be the elongated lobes found in roots of alfalfa and the clovers, or they can be round like those found on birdsfoot trefoil and soybean (Figure 8-8). Lobed nodules are perennial. They overwinter and fix nitrogen for more than one growing season, whereas round nodules die and reform on roots each year. Upon dissection, active regions of nodules will be observed to contain a pink pigment, leghemoglobin, that is responsible for oxygen regulation in the nodule. Nitrogen that is fixed by the bacteroids enters the plant's vascular system and can be transported throughout the plant.

Photoperiodism

Photoperiodism is a plant's reaction to changing durations of darkness. This response involves the pigment **phytochrome** that senses changes in amounts of red (absorption peak at a wavelength of 660 nanometers) and far-red light (absorption peak at a wavelength of 730 nanometers). Phytochrome has two interconvertible

forms, P_r and P_{fr}. The active form of the pigment is P_{fr} and is located in vegetative portions of plants and in seeds. Phytochrome is normally found in the cytoplasm of the plant cell, but when activated travels to the nucleus and induces changes in vegetative or floral cell production. There are several types of photoperiodic response. These include flowering, dormancy reactions, germination, leaf abscission, growth direction, and growth rate.

Flowering Response

Flowering in many plants is affected by photoperiod. Plants can be categorized by their flowering responses as **short-day**, **long-day**, or **day-neutral**. Some plants flower at the same time of year every year. These are either short-day or long-day plants (Figure 8-9). Short-day plants flower when the days are shorter than a certain time called a **photoperiod**. Long-day plants flower when the photoperiod is longer than a certain period. The main differentiation between "shorter than" and "longer than" is the length of the dark period or night.

Late summer or fall-flowering plants are short-day plants, and spring- or early summer-flowering plants are long-day plants. Short-day plants do not flower in the longest days of the summer (Figure 8-10). For example, to flower, strawberries must have a day not longer than 10 hours. Short-day crops include corn, soybean, cotton, and rice, all of which flower as the days grow shorter. Long-day crops include smooth bromegrass, wheat, flax, and mustards. Day-neutral plants, including ever-bearing strawberries, dandelion, cucumbers, and tomatoes, are not dependent on a certain photoperiod to flower. Day-neutral plants flower after a certain age or when a certain level of growth has been achieved, rather than in response to a photoperiod. An example is the garden petunia, which has been bred

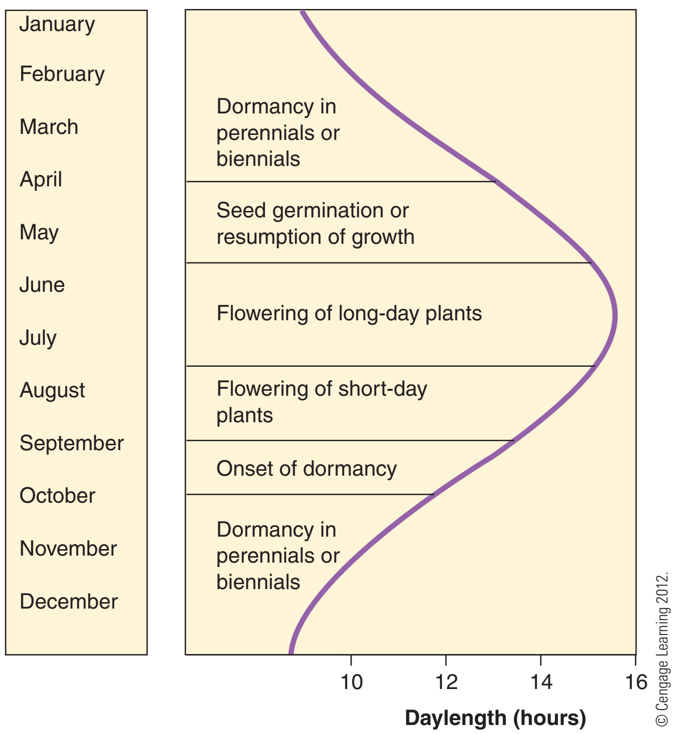


FIGURE 8-9
The flowering times for short-day and long-day plants in the northern hemisphere.



Discovering Phytochrome

In the early twentieth century, agricultural scientists H. Allard and W. Garner, who were studying tobacco and soybean, initially discovered and described photoperiodism, a plant's flowering response to different lengths of day and night. They were the first to categorize plants as flowering in "short day" or "long day". However, it took nearly 50 years for an understanding of exactly how plants recognize varying day lengths or darkness to be discovered. That trigger was the photoreceptor pigment phytochrome. A team of United States Department of Agriculture scientists working at Beltsville, Maryland, including H. Borthwick, a botanist; S. Hendrick, a chemist; and W. Butler, a biophysicist, first determined that soybean plants flowered and lettuce seed germinated in response to red and far-red light and also that the pigment was blue-green, based on the wavelengths it reflected. In addition, they determined the far-red to red reversibility of the pigment. The name phytochrome was derived from the Greek words for plant = *phyto* and color = *chrome*. Today, scientists know that there are five different kinds of phytochrome in plants and can identify their forms and functions.

to flower constantly. Plant breeders use their knowledge of photoperiod response and day length in a region to develop varieties of crops such as soybean that flower and mature within a growing season. Horticulturists use their knowledge of photoperiod response to produce timely flowering plants for consumer markets. For example, poinsettias, short-day plants, are grown under reduced day length so as to flower for the winter holidays.

Dormancy Response

In northern latitudes, perennial plants respond to shortening days and decreasing temperatures by undergoing a dormancy reaction. In alfalfa and perennial grasses, the dormancy reaction involves reducing herbage growth, storing energy in the roots and crowns, increasing sugar concentration in the cells, and forming crown buds for regrowth in the spring. In many trees, which are perennial, leaves drop (leaf abscission) in response to short days and form dormant buds that overwinter.

Seed Germination

Germination of many seeds is affected by photoperiod. Deeply buried seeds that are not exposed to light do not germinate. In contrast, those near the surface that receive appropriate amounts of light will germinate. Light that reaches germinated seed is received by phytochrome, which activates vegetative growth of the epicotyl toward the soil surface.

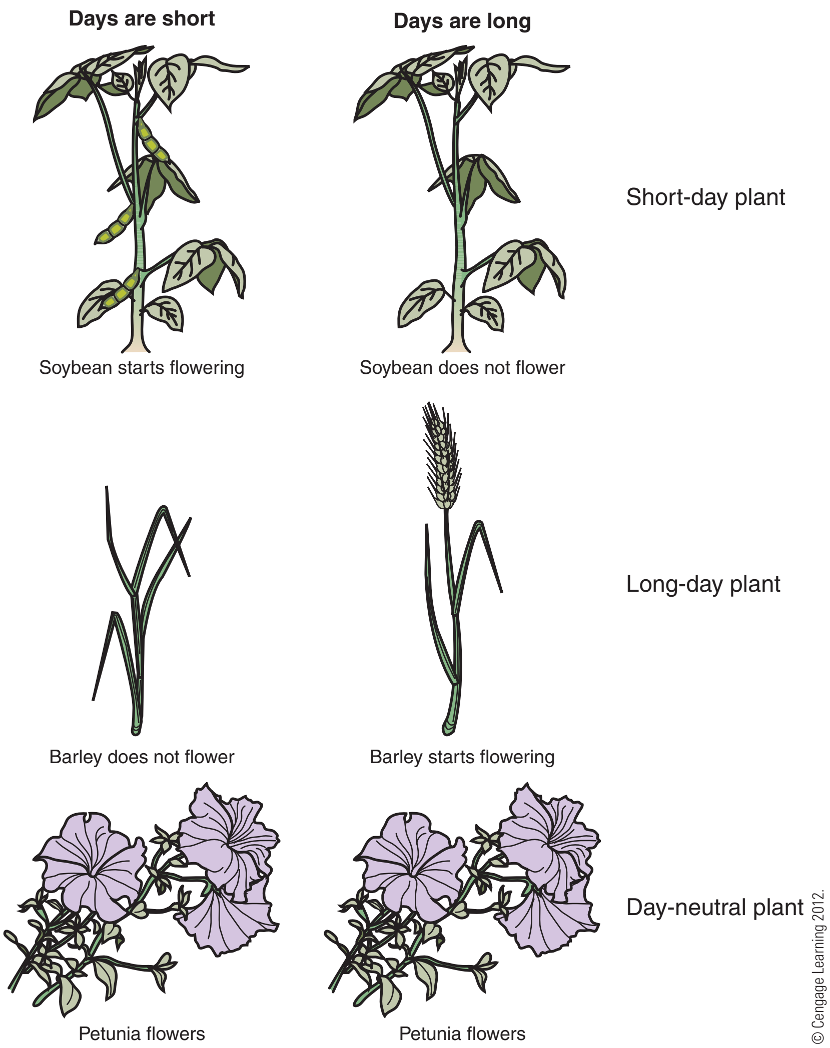


FIGURE 8-10 The effect of day length on long-day, short-day, and day-neutral plants.

Vernalization

Vernalization is a response during the winter that is important for triggering flowering in the spring. To flower in the spring, winter-annual small grains such as rye and wheat, along with perennial grasses such as smooth bromegrass and reed canarygrass, require exposure to short photoperiods and low temperatures during winter. Winter wheat and winter rye that are planted in the spring without vernalization will not flower.

Growth and Development

Plant cells use the carbon compounds produced during photosynthesis for metabolic processes including respiration and enzyme formation. A portion of that carbon is also used for growth of the plant. **Growth** is the irreversible increase in

weight or size of an organism due to an increase in number and size of cells. For example, growth would be the development of leaves and increase in height while the plant is vegetative. Growth is also associated with development. **Development** is the process of differentiation when plants transition from germination, seedling, vegetative, flowering, and seed-maturation states.

Dry-Matter Accumulation

Plant growth can be measured in terms of fresh weight and dry weight, in linear dimensions such as height, or by leaf area. Because of fluctuations in water content caused by the environment, dry weight is the most commonly used measure of growth. **Dry matter** is the weight of all the components of a plant minus the water. Dry matter accumulation changes with developmental stage (Figure 8-11). During early stages of plant development, the dry matter in leaves and stems increases linearly and then begins to plateau as plant energy is partitioned into seed development. At this point, the dry matter increases only in the seed. In examining a typical pattern of dry matter accumulation throughout a growing season, it is apparent that the proportion of dry matter in the root, stem, leaf, or fruit varies as the plant matures. The overall dry matter accumulation increases throughout the season until near maturity, when a slight drop in overall biomass occurs. Individual crops each have a unique dry matter accumulation curve throughout the season.

Measuring Development

As discussed in Chapter 7, the plant body is composed of shoots, roots, leaves, flowers, fruits, and seeds. The development of a plant starts from the seed (see Chapter 6). Once the seed germinates, the primary plant organs—the shoots and roots—develop first. From the shoots, the stem and leaves form and, after a certain time, the flowers, fruits, and seeds develop. The general developmental stages are seed, seedling, vegetative, flowering, fruit, seed, and senescence.

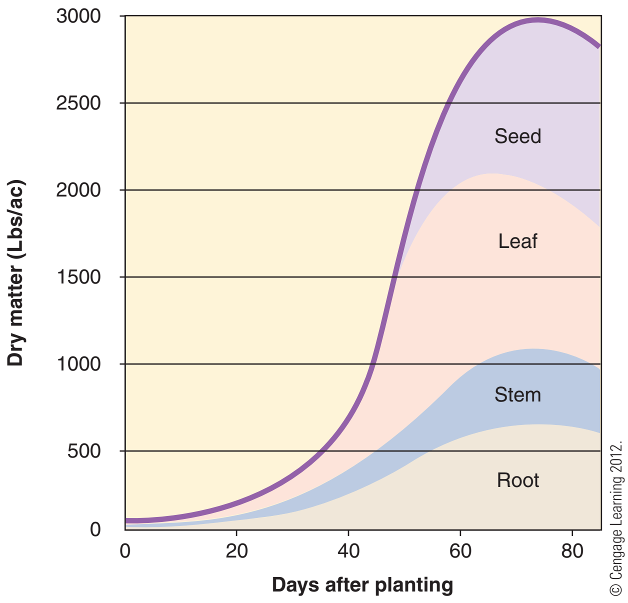
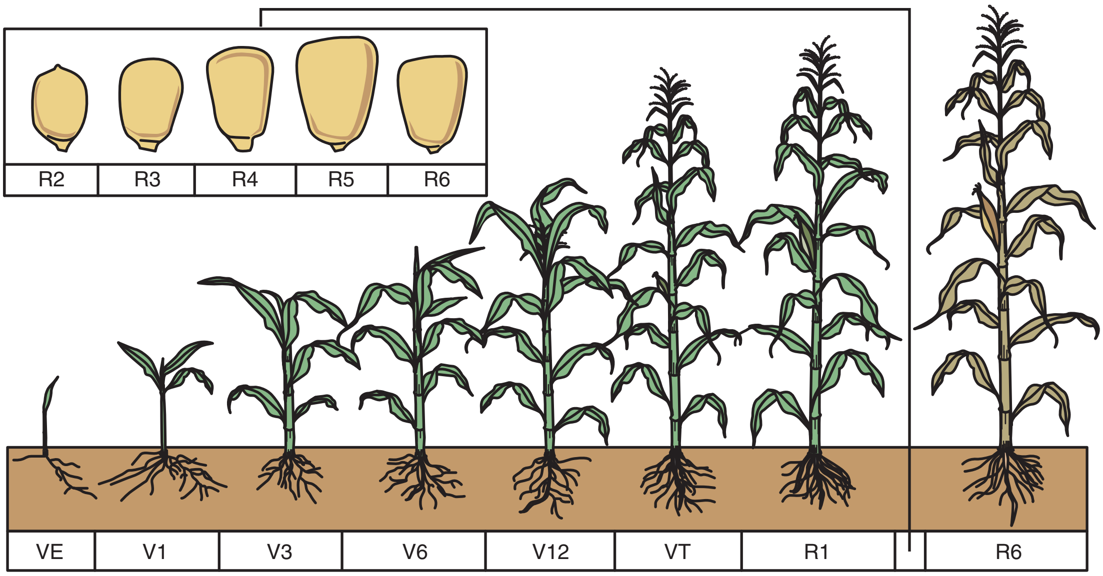


FIGURE 8-11 General pattern for partitioning of dry matter during plant growth. 1 pound per acre = 1.1 kilograms per hectare.

We can further break down the developmental stages of some crop species. A system called the **Feekes scale** measures development in cereals. The Feekes scale is a numerical system for assigning developmental stages. The scale goes from 1 (the first leaf stage) to 11 (the grain-ripening stage). Other systems include the Zadoks and Haun scales. Corn and soybean growth stages are shown in Figures 8-12 and 8-13. The corn and soybean growth scales shown are from Illinois State University. This system divides plant development into two stages: vegetative and reproductive. Vegetative stages are denoted by *V*, whereas reproductive stages are denoted by *R*. Alfalfa developmental stages are shown in Table 8-5.

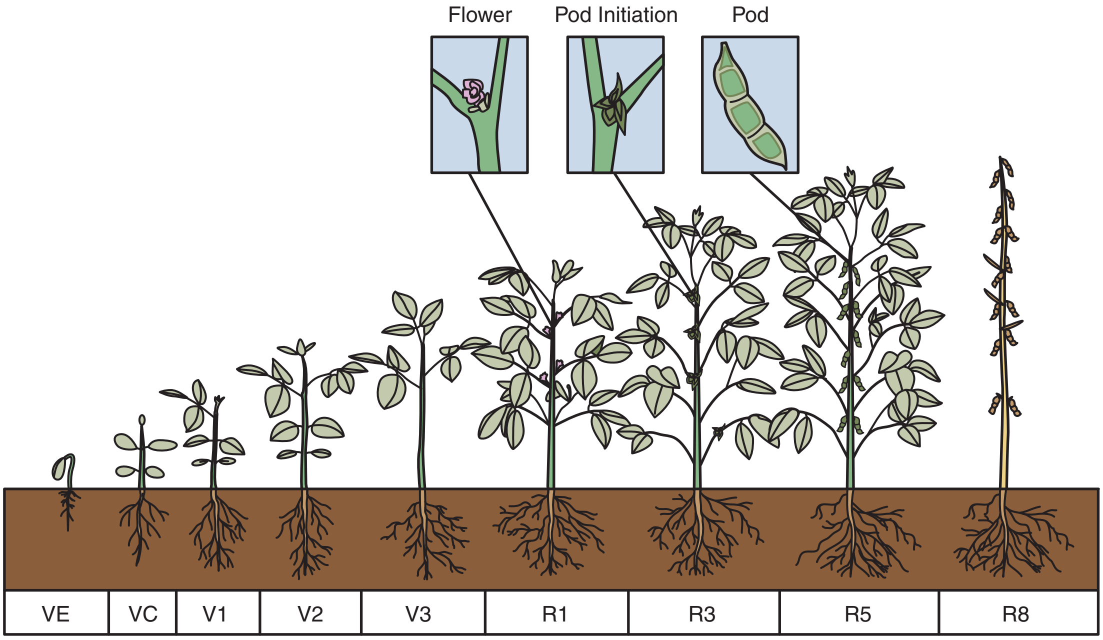
Scientists and farmers use crop growth stages to describe crop development and as a guide to when to apply management treatments. Alfalfa, for example, has different nutrient concentrations depending on the growth stage at which it is harvested. Some herbicides, pesticides, or mechanical weed control operations can be conducted only at certain crop development stages. Finally, farmers must harvest at the proper stage of maturity to maximize yields. To develop sound management strategies, especially of inputs, producers should understand development and its relationship to timing of procedures such as fertilization, irrigation, and harvest.



Vegetative Stages		Reproductive Stages	
Stage	Description	Stage	Description
VE	Emergence	R1	Silking
V1	First leaf	R2	Blister
V2	Second leaf	R3	Milk
V3	Third leaf	R4	Dough
V6	Sixth leaf	R5	Dent
V12	Twelfth leaf	R6	Physiological maturity
VT	Tasseling		

Adapted from University of Illinois Extension (2007).

FIGURE 8-12 Some of the developmental stages of corn.



Vegetative Stages		Reproductive Stages	
Stage	Description	Stage	Description
VE	Emergence	R1	One flower at any node
VC	Cotyledon growth stage	R3	Pod is 1/2 cm long with unrolled leaf
V1	Unifoliate leaves completely unrolled	R5	Seeds beginning to develop
V2	Leaves at node above unifoliate leaves unrolled	R8	Physiological maturity
V3	Three nodes with unrolled leaves		

Adapted from University of Illinois Extension (2007).

FIGURE 8-13 Some of the growth stages of soybean.

Growing Degree Days

Temperature is a primary factor in determining growth and development of plants. **Growing Degree Days (GDD)** is an index of heat accumulation (or heat units over time). Scientists and growers use GDDs to estimate how crop development will progress and when a crop is predicted to mature. It is based on the temperature as it progresses over time for a given location. For corn and soybean, both warm season crops, almost all growth occurs above temperatures of 50°F (10°C), and temperatures above 86°F (30°C) do not make the growth rate more rapid. The base temperature is 50°F (10°C), and any temperatures above 86°F (30°C) are considered to be equal to 86°F (30°C). Thus, to calculate GDDs the following formula is used:

$$\text{GDD} = \frac{\text{Maximum temperature} + \text{Minimum temperature}}{2} - \text{Base temperature}$$

TABLE 8-5

Developmental stages of alfalfa. *Adapted from Fick and Mueller (1989).*

Stage	Description
Vegetative phase: stems and leaves; no buds, flowers, or seedpods	
Early vegetative	Stem length ≤6 inches (15 cm)
Mid-vegetative	Stem length 6–12 inches (16–30 cm)
Late vegetative	Stem length ≥12 inches (30 cm)
Flower bud development: stems with flower buds	
Early bud	1–2 nodes with buds
Late bud	≥3 nodes with buds
Flowering phase: stems with open flowers	
Early flower	1 node with 1 open flower
Late flower	≥2 nodes with open flowers
Seed production: stems with flowers and seedpods	
Early seedpod	1–3 nodes with green seedpods
Late seedpod	≥4 nodes with green seedpods
Ripe seedpod	Nodes with mostly brown, mature seedpods

An example calculation for a day with a high of 80°F and a low of 60°F is [(80 + 60)/2] − 50 = 20 GDDs. Other crops besides corn and soybean will use formulas with different base temperatures. Cool season crops like wheat grow at lower temperatures, and a base temperature of 32°F (0°C) and a maximum temperature of 76°F (24°C) are used.

The GDDs for each day since the beginning of the season are added together to get the total GDDs. A very early season corn variety that takes 85 days to mature will require 2100 GDDs, while a full season corn variety that takes 130 days to mature will require 2900 GDDs. Therefore, the number of growing degrees it will take to reach the growth stages will vary depending on variety (Figure 8-11).

The Life Cycles of Plants

All plants are categorized as annual, biennial, or perennial (Figure 8-14). Life cycles are important in the production of crops and in the management of weeds.

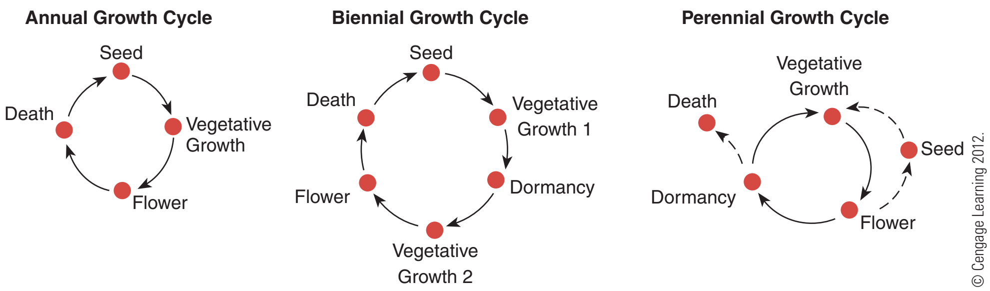


FIGURE 8-14 The life cycles of annuals, biennials, and perennials.

Annuals

Annuals are plants that complete their life cycle in one year or one growing season. The termination of their life cycle is seed production. Many of our most important grain crops are annuals. Annuals are dependent on regeneration of new plants from seed to start the next growth cycle. Transportation of seed to new environments is the primary approach to colonizing new environments. Two categories of annuals are summer annuals and winter annuals.

- Summer annuals are planted in the spring months, grow during the summer months, and mature during the late summer to fall. Crops include corn, soybean, spring wheat, and rice. Weeds include pigweed, velvetleaf, foxtails, and ragweed.
- Winter annuals are planted in the late summer to early fall, grow vegetatively before winter, overwinter in a dormant state, and flower in the spring. Winter annuals typically flower in response to the lengthening days in late spring. Crops include winter wheat, winter rye, and some canola varieties. Weeds include chickweed and wild mustard.

Biennials

Biennials are plants that complete their life cycle in two growing seasons. In the first year, biennials are vegetative and accumulate significant storage reserves in the fall of the seeding year. After overwintering, biennials flower, form seed, and die. Crops include sugar beet and sweet clover. Weeds include wild carrot and bull thistle. When harvested for processing to sugar, sugar beet roots are harvested in the fall of the seeding year and are not allowed to overwinter. Carrots, a horticultural crop, are also biennial.

Perennials

Perennials are plants that persist for three or more years or growing seasons. They typically flower each year but may remain vegetative throughout their lives. In northern, temperate climates, perennials typically undergo a dormant period in the winter and resume growth in the spring. To survive periods of dormancy, perennials often have some type of specialized energy-storage structure such as rhizomes in quack grass, fleshy taproots in alfalfa, or corms in timothy. Crops include alfalfa, white clover, smooth bromegrass, big bluestem, switchgrass, and hybrid Bermuda grass. Weeds include quack grass, johnsongrass, dandelion, and Jerusalem artichoke.

Pseudo-Annuals

Sometimes perennial and biennial plants are managed as annuals and could be considered **pseudo-annuals**. For example, sugar beet is a biennial plant that is harvested for sugar production after only one growing season. Cotton is a perennial plant, but in cropping systems it is only used as pseudo-annual. Alfalfa and red clovers are perennial plants that can be grown as annuals for use as a green manure crop.

Review Questions

1. How do plants manufacture energy?
2. Explain the process of photosynthesis and identify its products.
3. What is the overall chemical reaction of photosynthesis?
4. What are the light and carbon-fixation reactions of photosynthesis?
5. Explain the differences between C_3 and C_4 plants.
6. Why is cellular respiration important for plants? What is the overall chemical reaction that describes the process?
7. What is the process of transpiration?
8. Identify three important functions of transpiration.
9. How do plants regulate transpiration?
10. What is evapotranspiration?
11. Explain the process of symbiotic nitrogen fixation. Identify some crop plants that can conduct symbiotic nitrogen fixation.
12. What is the pigment responsible for photoperiodism in plants? Give some examples of photoperiodic responses by plants.
13. As grasses and legumes grow, they go through several, general-growth stages. Identify these.
14. What are Growing Degree Days and why are they used?
15. Describe the terms *annual, biennial,* and *perennial,* and give examples of crops in each category.

Critical Thinking

1. Explain why plants appear green to humans.
2. In previous chapters, we discussed the subject of global warming. How will increases in atmospheric CO_2 concentration and air temperature affect important processes such as photosynthesis and transpiration? Will crop yields increase?
3. Plants are uniquely adapted to our world. Using photosynthesis and photoperiodism as examples, explain how plants have adapted to the light received on the earth and the seasonal variation in light on the earth.
4. Why is it important to characterize the exact stage of a crop's development?

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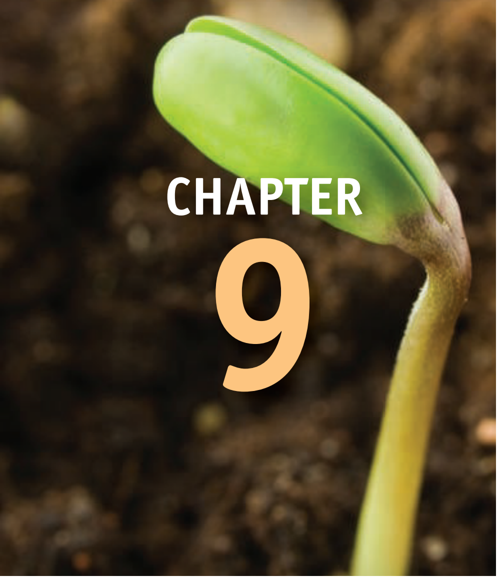
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CHAPTER 9
Improving Plants





Key Concepts

- Chromosomes, which control inheritance in all plants, are made of deoxyribonucleic acid (DNA), which is organized into units known as genes. It is the genes that will determine all metabolic activities of cells.
- Meiosis is the division of a cell into two new cells called gametes that have half the genetic content of the original cell.
- The external appearance of a plant is known as the phenotype, and the genetic makeup of a plant is the genotype. The proportion of a given phenotype that is due to genetic factors is known as heritability.
- Gregor Mendel's laws of inheritance are at the base of plant breeding because they enable the prediction of the outcome of crosses.
- One or few genes control qualitative traits, and several or many genes usually control quantitative traits.
- Sexually reproducing plants are either self- or cross-pollinated. A crop's type of pollination is important because it will determine breeding strategies that will be used in a breeding program.
- Collection, selection, crossing, evaluation, and introduction are the main steps of most breeding programs.
- Gene transformation allows for the transfer of one gene or several genes of interest into a plant with otherwise desirable characteristics; genes may originate from a wide range of sources, including bacteria and other nonplant sources.
- Most major crops have been genetically modified for herbicide or insect resistance.
- Recent advances in biotechnology have expanded plant breeders' capability to develop crops with new traits.

Key Terms

allele
Agrobacterium tumefaciens
biotechnology
chromosome
cross-pollination
cultivar
DNA
gamete
gene
genetic engineering
genetically engineered organism (GEO)
genetically modified organism (GMO)
genotype
heritability
heterosis
heterozygous
homozygous

hybrid
hybrid vigor
hybridization
inbred
mass selection
meiosis
molecular marker
mutation
pedigree selection
phenotype
polyploid
qualitative
quantitative
selection
self-pollination
stacked trait
transgenic

Introduction

Crop improvement through selection and breeding is a fundamental aspect of the development of modern agriculture. Crop improvement has been taking place since the earliest crop domestication. Crops have been selected for desirable traits, including seed size, improved yield, and pest resistance. Significant advances in crop improvement during the twentieth century were due to rediscovery of fundamental principles of genetics as described by Gregor Mendel and to the understanding of trait inheritance. Developments during the past century in plant breeding—combined with those in agronomy, plant physiology, molecular biology, and genetics—have contributed to technical advances that led to unprecedented yield improvements in all major crops (Figure 9-1). Crop scientists estimate that about half of the yield gains in major cereal crops have resulted from genetic improvement. The USDA-ERS estimates that for the United States alone, the net economic effect from genetic enhancement of major crops is about $390 million per year. Agricultural **biotechnology**, which consists of the scientific techniques used to create or transform plants, is now being used to add desirable traits to crops.

Reproduction in Plants

Reproduction in plants occurs via seeds, which result from the fusion of male and female reproductive cells, known as **gametes**, that are located in flowers (see Chapter 7). Sexually reproducing plants are either self- or cross-pollinated, or a mix of both systems (Table 9-1). **Self-pollination** occurs when pollen is transferred to the stigma in the same flower. Plants that are self-pollinators do not require another plant to set viable seed. With **cross-pollination**, the pollen fertilizes the ovule located on another plant. Strict cross-pollinators require an outside source of pollen to complete fertilization and set seed.

A crop's mode of reproduction determines breeding methods and strategies. Almost all major crops reproduce sexually. Though the vast majority of plants are cross-pollinated, many important crop species are self-pollinated (e.g., wheat and soybean). Some crops may be both self- and cross-pollinated (e.g., sorghum and cotton). Cross-pollination may be promoted by different mechanisms including: (1) pollen and stigma that mature at different times; (2) self-sterility or incompatibility, meaning that pollen from a flower cannot physiologically fertilize an ovule

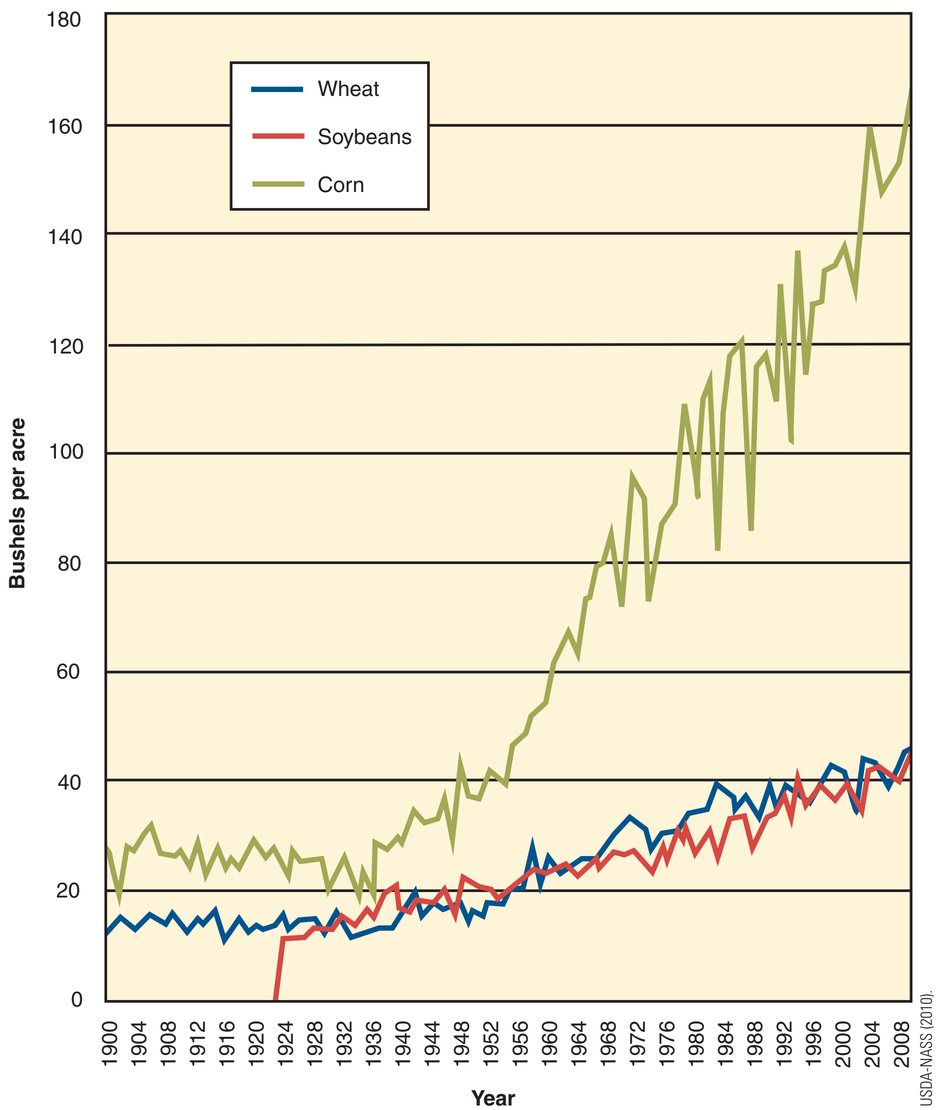


FIGURE 9-1
Yield improvement (bushels/acre) in the United States for wheat, soybean, and grain corn (1900–2009). 1 bushel/acre of corn = 63 kilograms/hectare and 1 bushel/acre of soybean or wheat = 67 kilograms/hectare.

from the same plant even if the pollen does come into contact with the stigma; (3) dioecious plants where the male and female flowers are on separate plants; and (4) monoecious plants that have imperfect flowers where the male and female reproductive parts are not contained within the same flower.

DNA, Chromosomes, and Genes

To understand how plants are improved, we must learn some basic genetics. Genetic processes occur within cells. Plant cells have three basic components: the cell wall, the cytoplasm, and the nucleus (see Figure 8-1 from Chapter 8). The cytoplasm contains various organelles that have important specific functions in plants. The nucleus contains **chromosomes** that control inheritance. Chromosomes are made of deoxyribonucleic acid **(DNA)** that is organized into units known as **genes**,

TABLE 9-1

Reproduction in some common crop species.

Self-pollinated	Cross-pollinated	Both self- and cross-pollinated
Barley	Alfalfa	Amaranths
Chickpea	Apple	Broadbean
Coffee	Bromegrasses	Cotton
Cowpea	Clovers	Cucumber
Flax	Corn	Foxtail millet
Jute	Mustard	Lupines
Pearl millet	Onion	Peach
Oat	Potato	Pigeon pea
Pea	Rye	Sesame
Rice	Ryegrasses	Sorghum
Safflower	Safflower	Squashes
Soybean	Strawberry	Watermelon
Tobacco	Sugarcane	
Tomato	Sunflower	
Triticale	Timothy	
Wheat		

which determine all metabolic activities of cells. Chromosomes contain hundreds to thousands of genes. DNA, and therefore genes, is composed of units known as *nucleotides*. The sequences of these nucleotides dictate the sequence of amino acids during protein synthesis (amino acids are the units that make up proteins).

Chromosome Number and Meiosis

Genetic material is transmitted through two major processes: mitosis and meiosis. Mitosis is the division of a cell into two new cells that are identical to the initial one, a process that is critical to growth and development. **Meiosis** is another type of cell division that reduces the genetic content by half (Figure 9-2). Meiosis is associated with sexual reproduction and occurs in the male and female reproductive organs (i.e., the anthers and the ovaries). The reduction by half of the genetic material ensures that upon fertilization, embryos will maintain the same quantity of genetic material as the parents, half inherited from the male parent, and the other half from the female parent.

Every species has a specific number of chromosomes. Chromosomes occur in pairs so that cells of most plants contain two copies of each chromosome and are known as *diploids*. Often diploids are represented by the code 2n, where *n* refers to the number of different chromosomes. The *n* number of chromosomes varies from

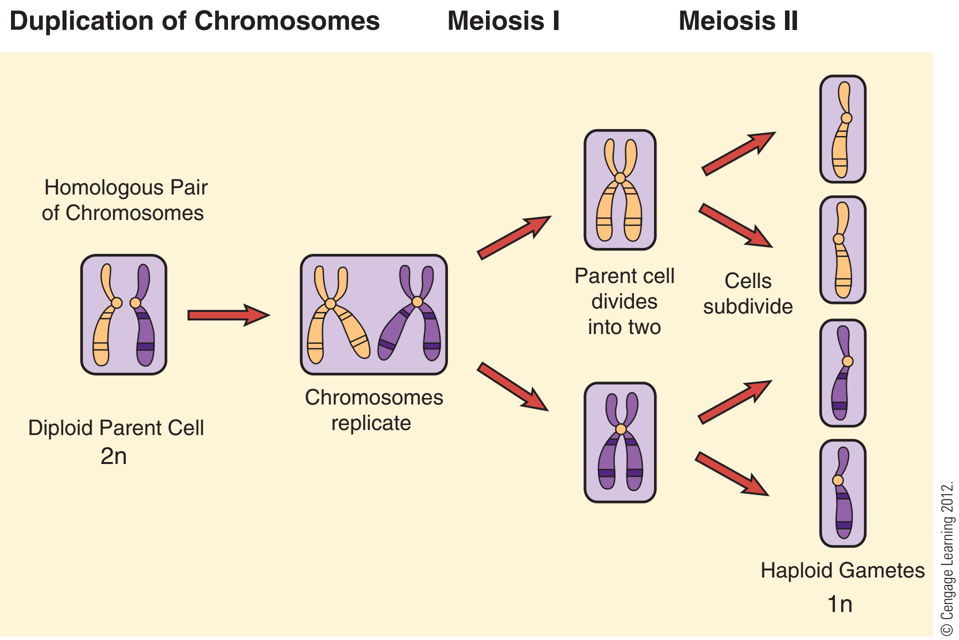


FIGURE 9-2
The process of meiosis. The parent cell (2n) divides twice to produce four haploid (1n) cells.

one species to another. However, some species may have more than two copies of each gene (e.g., alfalfa and wheat) and are known as **polyploids**. For example, a tetraploid has four copies of each chromosome (4n), and a hexaploid would have six (6n).

Homologous chromosomes are chromosomes with genes that control the same function and that are at the same location, or locus. When a gene that controls a certain trait has alternative forms, the different forms are called **alleles** and they can have differing effects. One of the chromosomes in a diploid organism was originally inherited from the female parent, the other from the male, and thus, in homologous chromosomes, the exact composition of a gene may differ. At the end of meiosis, a total of four new haploid cells are produced, each with half of the genetic material originally contained in the parent cell. The exact composition of genes in these haploid (1n) cells differs due to recombination. This variation is the basis of Mendelian genetics (see further discussion later in this chapter) and is the source of variation among progeny of two individuals.

Phenotypes, Genotypes, and Heritability

Variation among populations of the same species is due to environmental and genetic factors. **Genotype** is the total genetic makeup of a plant. The **phenotype** of a plant is due to its genotype, the environment, and their interaction. The proportion of a given phenotype that is controlled by genetic factors is known as **heritability**. Breeding and selection for a particular trait is enhanced with greater heritability. Some simple traits such as flower color are discrete and easily identified in a range of environments. These traits are **qualitative** and are often controlled by one or a few genes. More complex traits are **quantitative** and are often controlled by several genes. Examples of quantitative traits include biomass, grain yield, and winter hardiness.

Heritable (or genetic) variation observed in a population originates from several sources, including random gene recombination during meiosis and gamete formation, gene mutation, or chromosomal aberrations. A **mutation** refers to a sudden heritable change in the nucleotide sequence of a gene. Chromosomal aberrations are deletions or rearrangements of large sections of chromosomes. Such aberrations often occur during pairing of homologous chromosomes at meiosis; each chromosome from a given pair may exchange part of their genetic material. Genetic variation is the ultimate source of new materials for plant breeding.

Mendelian Genetics

Gregor Mendel (1822–1884) was an Austrian monk who first reported in 1865 that it is possible to predict the visual appearance of pea plants resulting from the crossing of two different pea plants. His observations led to the formulation of the laws of inheritance, which still apply to plant (and animal) breeding today. The laws of inheritance are based on the predictable behavior of chromosomes and transmission of genes from parents to offspring. They are based on three factors: (1) genetic characters are controlled by two alleles, which can take one of two forms on each of the homologous chromosomes; (2) when two different alleles are present, one determines the phenotype observed for that trait (that allele is said to be dominant, the other recessive); and (3) during meiosis, one of the chromosomes from the parent will be passed on randomly to each of the gametes. Based on these three principles, we can predict the outcome of crosses.

Mendel worked with crossing peas, which are self-pollinating. In Figure 9-3, two **homozygous** pea plants (i.e., they have the same allelic form on both homologous chromosomes)—either green pods (*GG*) or yellow pods (*gg*)—are crossed. Because they are homozygous, all gametes of the green-pod parent carry the *G* allele, and those of the yellow-pod parent the *g* allele. Their progeny is called the F_1 generation, which indicates the offspring of the first cross. This F_1 generation will all be **heterozygous**, meaning that they have both forms of the allele (i.e., genotype is *Gg*). Because the *G* form of the allele is dominant, all plants among the F_1 generation will have green pods (i.e., their phenotype is green pods). Also, if considering only this trait, during gamete formation, all plants will produce two types of gametes, *G* or *g*. Thus, if two individuals of the F_1 generation are crossed (i.e., F_1 cross), there will be three possible genotypes among their progeny (i.e., F_2 generation): *GG*, *Gg*, and *gg*. The ratio of these genotypes (i.e., genotypic ratio) will be 1:2:1 for *GG*, *Gg*, and *gg*, respectively, giving a phenotypic ratio of 3:1 green:yellow.

These simple principles also apply if more than one trait is combined, as seen in Figure 9-4, where two traits—pod color (green or yellow) and seed color (green or yellow)—are combined. When dealing with multiple traits, it is often easier to use a Punnett square to visualize genotypes and phenotypes resulting from the random recombination of gametes during fertilization. Figures 9-3 and 9-4 both illustrate the use of Punnett squares to present the progeny of a cross for one or two traits.

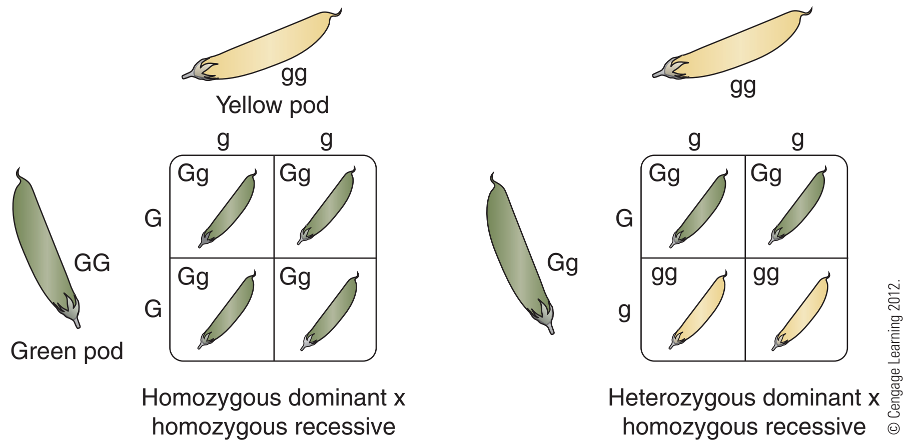


FIGURE 9-3 Basic Mendelian genetics. Shown here are two example crosses of pea plants. The symbols *G* (dominant) and *g* (recessive) designate green pod and yellow pod alleles, respectively, in the genotype of mature plants and gametes. The first example shows a homozygous plant with green pods (*GG*) crossed with a homozygous plant (*gg*) with yellow pods. The offspring in this case will all have green pods. The second example shows a heterozygous plant with green pods (*Gg*) crossed with a homozygous plant with the recessive trait for yellow pods (*gg*). Half the offspring will have green pods, and the other half will have yellow pods.

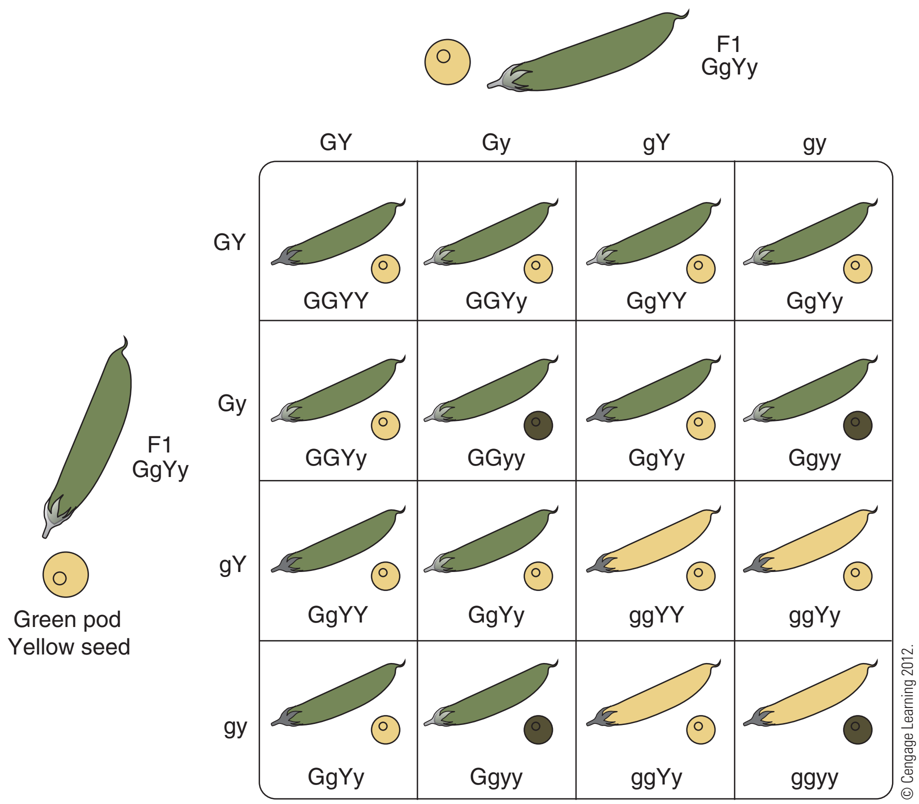


FIGURE 9-4 Basic Mendelian genetics. Use of a Punnett square to visualize the phenotypes and genotypes of the F_2 generation resulting from a cross involving two traits (i.e., color of pods and color of seeds). As in the previous figure, *G* indicates the dominant allele for green pods, and *g* is recessive for yellow pods. The symbol *Y* denotes the dominant allele for yellow seeds, and *y* indicates the recessive green seeds.

Quantitative Inheritance

Qualitative traits can be easily separated into distinct classes, such as green or yellow pods or seeds in pea plants. These traits are controlled by one or a few genes, and thus their phenotypes can be easily distinguished. Although some economically important traits are qualitative (e.g., seed color, disease resistance), most important traits such as seed yield and quality are continuous and cannot be segregated in distinct classes. These traits are known as quantitative traits. Other examples of these traits include height and growth rate. These types of traits are usually controlled by several or many genes and are usually greatly affected by environmental factors. Thus, studying them and predicting their inheritance is more challenging. However, each individual gene segregates according to Mendel's laws described earlier. Usually with quantitative traits, the cross between two homozygous parents will lead to F_1 offspring with intermediate values.

Figure 9-5 illustrates the hypothetical inheritance of height. In this example, height is a quantitative trait with three genes involved. The alleles from each A, B, and C contribute 4, 8, and 4 centimeters to the height, whereas the alleles a, b, and c each contribute 2 centimeters. A plant with the genotype AABBcc will be 28 centimeters, and a plant with a genotype of aabbCC will be 16 centimeters. Gametes produced by the F_1 generation will be *ABC*, *ABc*, *AbC, aBC, abc, abC, Abc, AbC,* and *aBc*. After crossing, there are 64 possible genotypic combinations in the F_2 offspring, with phenotypes that range from 32 to 12 centimeters. In this example, genes affecting the qualitative trait are said to be additive, referring to the fact that each gene equally and independently affects the phenotype. Of course, environmental effects are also a factor in a trait such as height.

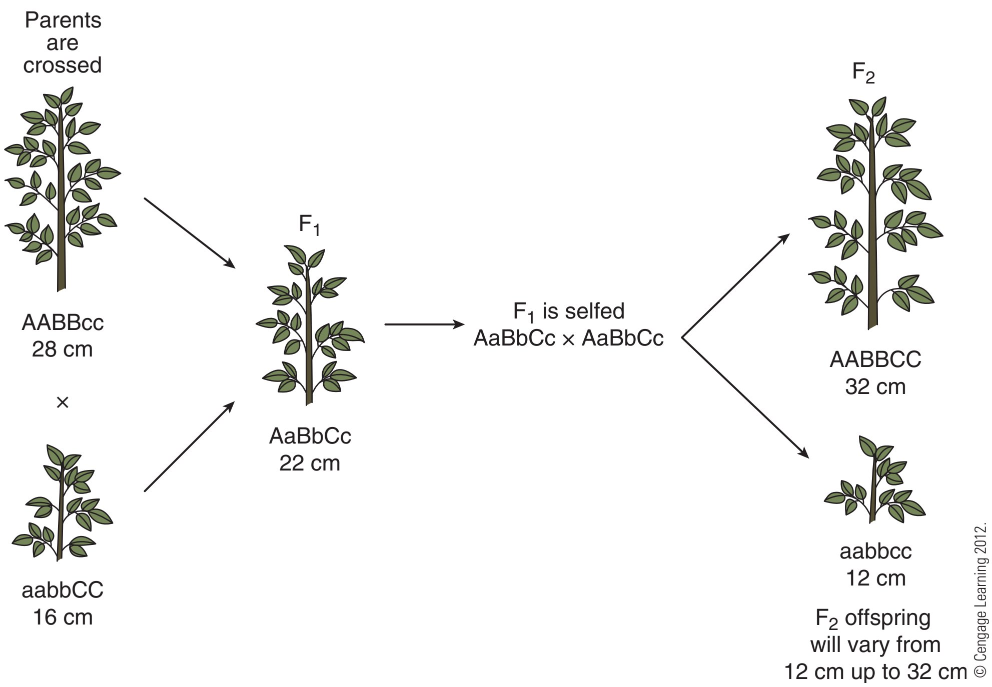


FIGURE 9-5 Inheritance of quantitative traits. The larger variation in the F_2 in relation to the F_1 generation is due to gene segregation and recombination, which did not take place in the F_1 generation because it was the result of the cross of two homozygous parents. The F_2 generation can display all heights between 12 and 32 centimeters.

Plant Breeding

Humans have practiced aspects of plant breeding since they first domesticated crops by selection of desirable plant types from among wild populations. Early on, people noticed the heritable variation in plants. The fact that "like breeds like" (i.e., offspring tend to resemble parents) was the theory guiding selection. Some of our modern crops, for example, corn, bear little resemblance to their wild predecessors because of thousands of years of human selection (see Chapter 1). As agriculture developed, farmers selected seed from superior plants and used it for subsequent planting. This approach resulted in the development of "land races" or land "varieties." An example was the alfalfa brought to Minnesota by the German immigrant Wendelin Grimm. Grimm selected it based on persistence. Seed was harvested from stands that persisted on Grimm's Minnesota farm and developed into Grimm alfalfa. This was the first winter-hardy variety of alfalfa in the Midwest and was widely grown by farmers.

Today, plant breeders improve plants by using specific techniques that are based on an understanding of genetics. The key objective of every breeding program is to develop superior cultivars compared to existing cultivars. ***Cultivar*** is an internationally recognized term that refers to a group of genetically similar plants that may be distinguished from other groups of plants within the same species.

Plant Breeding Goals

Before initiating a breeding program, one must establish specific goals and objectives. These goals depend on the crop and the potential use of the plant product. Some example objectives include yield, quality traits, harvestability, and persistence.

Yield

Grain and forage yield are general goals of many breeding programs. Yield is a complex quantitative trait that has been improved by selection for disease and insect resistance, competitiveness, and drought tolerance. This breeding is responsible for the tremendous worldwide improvement in crop yields. Breeding programs have successfully developed cultivars with resistance to many diseases (see Chapter 16).

Quality Traits

Grain and forage quality traits include selection for starch fermentation characteristics and forage digestibility. These selected traits include the following:

- Forage crops such as alfalfa, corn, and perennial grasses have been selected for increased leafiness to increase feeding value, because leaves are higher quality than stems.
- Barley has been selected for grain with improved malting characteristics to influence the quality of beer.
- Wheat has been selected for grain with improved bread-making quality such as gluten content and starch characteristics.

- Corn and soybean have been selected for variable total oil content and oil characteristics.
- Cotton has been selected for increased fiber quality and color.

Harvestability

Harvestability traits are related to yield but are specific crop modifications that may reduce loss of the crop produced.

- **Lodging resistance.** Lodging (falling over) of a grain crop before it is ready to be harvested can cause significant losses in the crop's yield and quality. Lodging is a problem in all grain crops when the stem cannot support the grain that is produced. A grain crop can have a high yield, but if the crop falls over before harvest, the crop will be lost. Lodging can be reduced by selecting for stalk strength, dwarf character (short stems), and resistance against insects that damage the stalk.
- **Uniformity of maturity.** Most modern varieties of plants mature at a similar rate to allow for harvesting of the field at one time to maximize yield.
- **Shatter resistance.** Shattering is the loss of seed from the head of a grain crop before harvesting. In the wild, shattering is a survival strategy for a species, but it can greatly reduce crop yields if a coordinated harvest is desirable.
- **Dry down rate of grain.** Increasing the dry down rate of grain in the field is important to allow earlier harvest of the crop and less field loss.

Persistence

Persistence is a trait that is most often applied to perennials and, to a limited extent, to annuals. Enhanced persistence or survivability over the long term is particularly important for a perennial crop such as alfalfa. Selection for increased disease resistance and winter hardiness has increased the persistence of alfalfa throughout North America.

Plant Breeding Strategies

Once the goal of a breeding program has been chosen, a plant breeding strategy needs to be determined. Specific strategies will depend on method of reproduction (i.e., sexual or asexual), pollination (i.e., self- or cross-pollinated), and on the actual species. The basic steps in most breeding programs include: (1) collection of genetic materials, (2) selection of plants for the breeding program, (3) hybridization (i.e., crossing) of plants and reselection of superior progeny, and (4) evaluation of the new materials (Figure 9-6). Various aspects of the program are conducted in diverse environments because of the influence of factors such as precipitation, temperature, and soil fertility on expression of traits.

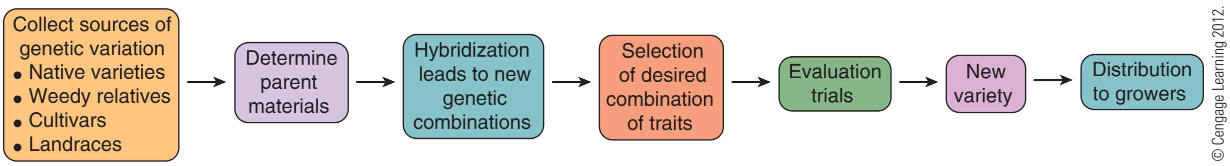


FIGURE 9-6 Generalized plant breeding strategy.



Plant Explorers

Crop improvement has been an important part of our agricultural success in the United States. Plant exploration and collection have provided genetic plant materials to use for the development of improved crops for agronomic and horticultural use. The importance of this effort was first recognized in the late nineteenth century. In 1898, the USDA established the Office of Foreign Seed and Plant Introduction for the purpose of promoting agricultural exploration. Since then, dedicated plant explorers and collectors have roamed the world in search of new crops for the United States. These explorers often travel in underdeveloped lands and suffer disease, wild animals, extremes of weather, and internal strife to hunt for plants. There have been many explorers, and two exceptional examples are Frank N. Meyer and Neils Hansen.

Frank N. Meyer was born in Amsterdam and at an early age became an avid student of botany and gardening. He immigrated to the United States in 1901 and conducted his first expedition with the USDA in 1904. He explored Europe and Asia, collecting a diversity of horticultural, ornamental, and agronomic plant materials. In the course of his career, he collected more than 2500 plant specimens including alfalfa, soybean, zoysia grass, peaches, grapes, and bamboo. The Meyer lemon and Meyer zosyia grass sold today are named after Frank. He died unexpectedly of suspicious causes on June 1, 1918, as he traveled down the Yangtze River, never returning from his fourth expedition to China. However, the specimens from his final trip did survive and were sent to the United States. In recognition of his life and accomplishments, the Crop Science Society of America presents the Frank N. Meyer Medal for Plant Genetic Resources for distinctive service to the National Plant Germplasm System.

Neils Hansen, a professor of horticulture at South Dakota State University, explored from 1898 to 1924 for the USDA and for the state of South Dakota. He especially searched for plants that were adapted to the severe climates of the northern plains. He traveled across Russia, Siberia, and China in search of plants. He collected forage plants such as alfalfa, smooth bromegrass, and wheatgrass, as well as horticultural crops. His collection of yellow-flowered *M. falcata* from Siberia brought a new, hardy alfalfa variety, Cossack, to the Dakotas. His work with pears, cherries, plums, and grapes was also noteworthy. He used these plant collections in his breeding program to develop new varieties of grapes, crab apples, and pears that could be used throughout South Dakota.

Today, the USDA-ARS National Plant Germplasm System still conducts targeted plant exploration. The USDA also preserves seeds and other plant parts of worldwide collections, new and old varieties, and weedy crop relatives. The collection includes 450,000 items that are housed at more than 20 specialized sites throughout the United States. Information on all the germplasm resources available is publicly available through the Germplasm Resources Information Network (GRIN) at <www.ars-grin.gov/>.

Assembling Genetically Diverse Breeding Materials

Collection of genetic materials is the first step in a breeding program and consists of assembling a collection of seeds from a range of sources, usually with the goal of maximizing variation for a specific trait such as disease resistance. The largest genetic diversity for a given species is usually found in its center of origin (see Figure 1-5 in Chapter 1). Plant explorers travel the world for sources of traits to be used in breeding programs.

Collections of seed from improved genetic material as well as plant introductions from foreign countries are now available in centralized university and governmental facilities (e.g., the National Plant Germplasm System of the Agricultural Research Service). These germplasm seed collections are from a range of locations. Breeders use germplasm collections to identify plants with desirable traits and attempt to combine them into new cultivars. Breeders may also start the breeding process with already established cultivars.

Selection

Selection is the process where breeders recognize and select individual plants with superior characteristics from a larger, variable population. Breeders thus have to select parents before performing any cross (i.e., hybridization) and also to select desirable phenotypes and genotypes among the resulting progeny.

Crossing

Hybridization is the process of crossing two plants to combine desirable characteristics from the two parents. This involves transfer of pollen from one plant to fertilize the egg of another. Specific strategies for self- and cross-pollinated crops are discussed in the following sections.

Evaluation of New Plant Materials

A breeding program's final products are grown as experimental entries in diverse environments. If the experimental entry performs favorably and has distinguishing features when compared to commonly used cultivars, it may be released as a commercial cultivar and sold to producers. The development of a new cultivar is lengthy and averages five years, but it may take up to 12 years after the initial cross.

Breeding Self-Pollinated Plants

Self-pollinated plants are usually genetically homozygous with both alleles of a given gene being identical (i.e., either *AA* or *aa*, but not *Aa*). Thus, variation among the progeny of a self-pollinated individual will be limited. To generate variation in self-pollinated plants, the plants must be hybridized by manipulating normally

Seed Banks

The United States began saving plants and seeds with interesting characteristics in the 1890s at stations across the country. In 1958, the National Seed Storage Laboratory in Fort Collins, Colorado, was built to consolidate the collections. Today, the facility, now named the National Center for Genetic Resources Preservation, contains plant germplasm as well as animal, microbe, and insect germplasm. Examples of materials preserved include modern and older crop cultivars, landraces, wild populations, and crop relatives. This facility also contains a large collection of important horticultural and landscaping plants that are grown, maintained, and researched at cooperating institutions around the country. Seeds preserved in cold storage (liquid nitrogen) have a 20- to 50-year life expectancy, but they do require periodic testing and replanting. Cooperating facilities around the country specialize in specific plant species (Figure 9-7). Facilities include:

- Aberdeen, Idaho. The National Small Grains Collection is housed at this location. Crops include barley, oats, rice, rye, wheat, and other grains.
- Urbana, Illinois. This facility stores the national corn and soybean collections.
- Griffin, Georgia. This site stores a diversity of crops including sorghum, eggplant, peanuts, peppers, sweet potato, and millet.
- Riverside, California. This facility houses the U.S. citrus collection including budwood of oranges, grapefruit, and lemons. It also stores germplasm of dates.

It is important to preserve the genetic resources of these existing collections, as well as to encourage efforts to preserve genetic resources from centers of origins. These materials are invaluable to plant breeders as new diseases and pests evolve and new crop traits are needed.



FIGURE 9-7 Locations of germplasm repositories in the United States.

self-pollinating plant flowers to avoid self-fertilization. This is usually done by removing anthers from the female parent and applying pollen from the father plant onto the stigma of the female. Once the cross is done, the resulting progeny (seed and plants) will be genetically heterozygous (i.e., *Aa*) for all genes.

Pedigree Selection

Pedigree selection is a selection method commonly used after hybridization of self-pollinating plants (Figure 9-8). The steps in this method are as follows:

- Seed from the initial crossing of the two selected plants (F_1 generation) is planted. Those resulting plants that appear superior are selected.
- Seed from these selected plants will be collected and will be planted in rows. Each row is produced from seed of a single plant. Undesirable plants will be discarded.
- Additional selection of plants within rows occurs with additional planting of selected seed as many as six times, to the F_6 generation (Figure 9-8).

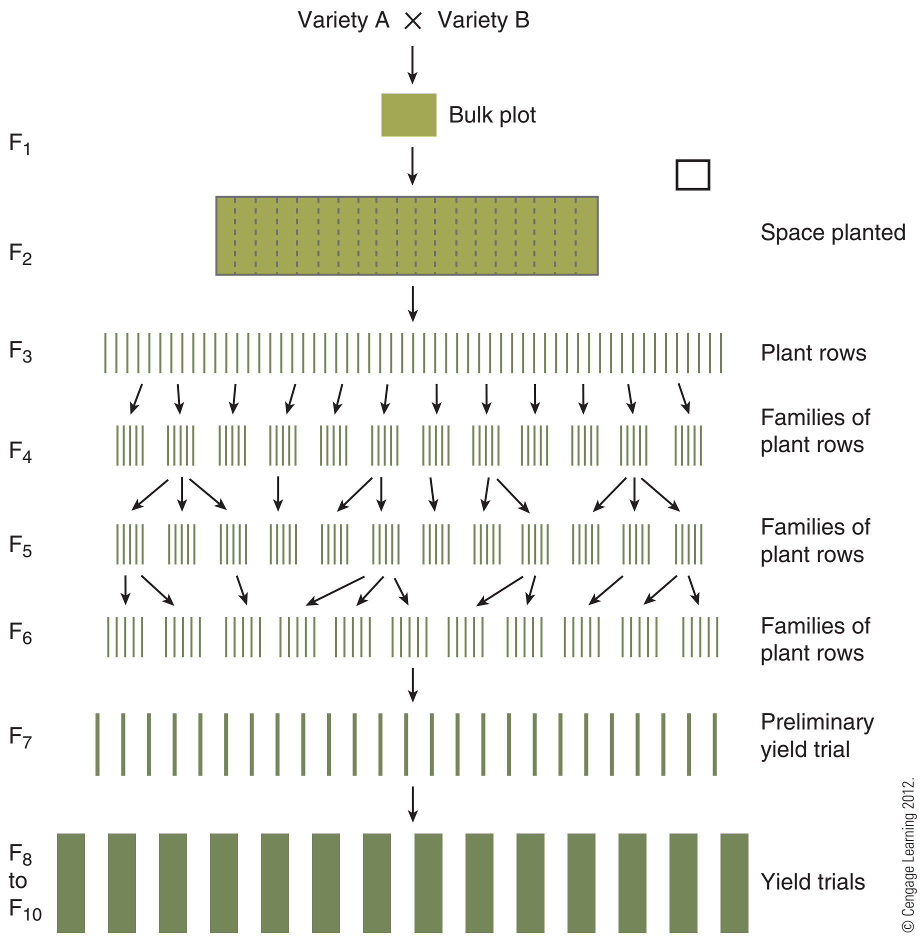


FIGURE 9-8 Pedigree selection method. All plants upon the initial cross are self-pollinated. From selected F_2 plants, progenies of 25–30 plants are grown in rows in F_3. Superior plants from the best rows are selected and planted in families of plant rows in F_4 to F_6, with selection being made of best plants, in best rows, and of best families. By F_6, families should be uniform. Preliminary yield trials are planted in F_7, and yield trials are continued through F_{10}.

- At the F_6 generation, families of plant rows become uniform, and seeds from a selected family of rows can be bulked and evaluated in yield trials. These yield trials will then determine if selected lines (i.e., bulked families of rows) are superior to existing cultivars and if they have desirable characteristics.



University of Minnesota Oat Breeding Program

Oat has been an important crop in the Midwest since European settlement. Oat improvement through breeding has occurred since the early 1900s. Breeders distributed the first variety, 'Minota,' to growers in 1903. Scientists developed more than 30 additional varieties with significant improvement in disease resistance and yield throughout the twentieth century and into the twenty-first. Farmers grew 'Gopher' (1923), 'Andrew' (1949), 'Lyon' (1977), 'Starter' (1986), 'Richard' (2000), and 'Sesqui' (2001) on significant hectares within the Midwest. Today, breeders still seek improved varieties with increased crown rust resistance, grain and milling yield, nutritional quality, and lodging resistance. Scientists also are selecting varieties for use in organic systems and in conventional systems with low levels of purchased inputs such as nitrogen. Following is the strategy for development of oat varieties at the University of Minnesota.

1. The oat breeding effort begins with establishing and then continually updating a specific objective statement that identifies the traits of interest in priority order. These include the factors listed previously.
2. Identify potential, parental oat germplasm that possess desired levels of one or more of the targeted traits listed in the objective statement. Researchers obtain parental breeding materials, including cultivated oats or wild oats, from other oat researchers throughout the world. They then visually evaluate these potential parents at two or more locations to provide environments that will optimize the expression of the traits of interest.
3. Upon identifying suitable parental genotypes, selected pairs of possible parents are crossed to produce F_1 hybrid seed. This crossing is done in the greenhouse, mainly in November, by manually transferring pollen from selected male parents to the stigmas of selected female plants one or two days after removing their anthers. The F_1 seeds are harvested about one month after crossing. Somewhere between 200 and 300 crosses intended to produce possible new varieties will be made. The F_1 seeds from the November crosses are planted in the greenhouse in January, and all F_2 seeds are harvested from individual F_1 plants in late April to early May. These seeds represent the first segregating generation (F_2) and are used in the next step of the program.
4. The F_2 seeds from step 3 are planted in the field in mid-May on the St. Paul campus of the University of Minnesota. There will be as many as 20–25 rows of 50 seeds each from an F_1 hybrid combination. In this

(*Continued*)

F_2 generation, selection begins in earnest. Plants that appear to possess the desired levels of appropriate traits are identified for harvest as individual plants (F_3 seed). This effort begins what breeders refer to as the pedigree method of selection, which works well for highly heritable traits. An important trait in the Minnesota program is crown rust resistance. Therefore, the F_2 nursery is artificially inoculated with the causal fungal pathogen. Other traits under consideration include maturity, height, standability (lodging resistance), seed color, and general grain quality, as well as resistance to a diversity of diseases.

5. Researchers visually evaluate the seed from every harvested F_2 plant of selected crosses, and seed from the selected plants is sent to New Zealand in September or October for a second field planting in the same year. Here, using the data collected earlier in the season, combined with visual evaluations made when the plants are near maturity, the breeders make harvest decisions. Five random panicles are taken from each selected plot, and the remainder of the plot is also bulk harvested. After the F_4 seed is returned to Minnesota, the bulked seed of the plot is visually evaluated, and seed from only the thrashed panicles that correspond to the selected bulks is visually evaluated. The F_4 seed from the saved F_3 panicles is then planted as F_4 rows in an inoculated crown-rust nursery at St. Paul in April.

   F_2 seed from unselected crosses (those not sent to New Zealand) may be advanced one generation in the greenhouse during the fall or winter months, and visually selected for inclusion in the inoculated rust nursery planted in early spring the following season.

6. The family/individual plant selection process continues until the F_5 or F_6 generation, when individual rows are bulk harvested because they look uniform as a result of the increased genetic homozygosity resulting from self-pollination. Following the F_5 or F_6 generation, selected lines are included in Preliminary Performance Trials at two locations, which include the first actual grain yield measurements. These materials are also subjected to several inoculated disease screenings in addition to several agronomic evaluations. Survivors "graduate" to multiple location Advanced Yield trials, then to the State Variety Trial, and then to regional nurseries in several states and in Canada. Nearing the end-of-the-line testing stage, a line purification process is invoked to begin the next stage, that of Seed Lot purification, and subsequent multiplication in preparation for variety naming and release.

Because new crosses are made and added to the system every fall and spring greenhouse season, there is always material in the program at every stage. This approach ideally generates a new variety every year or every other year.

Text contributed by Dr. Deon Stuthman, University of Minnesota.

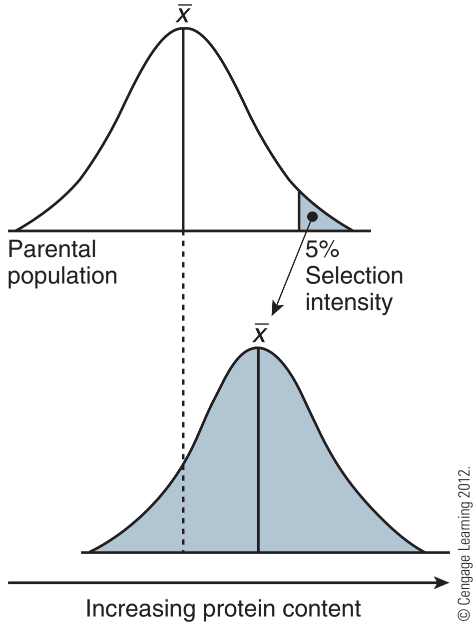


FIGURE 9-9
Impact of recurrent mass selection in a cross-pollinated crop. In this example, the objective is to increase protein content of a forage species. The plants in the top 5 percent of protein content are selected, and their seeds are used to grow the next generation. The resulting generation has a greater mean protein content when compared to the original parental population.

Mass Selection

Mass selection is one of the oldest and simplest approaches to plant breeding. **Mass selection** can be used with self- and cross-pollinated crops. It consists of the selection of individual plants with desirable characteristics. Seeds of selected plants are then bulked and used to grow the next generation. Selection is usually repeated for several generations. When selection is repeated, it is known as *recurrent selection* (Figure 9-9).

Breeding Cross-Pollinated Plants

Breeding and selection methods used for cross-pollinated crops often differ from those for self-pollinated plants. Because of the large amount of genetic variation (heterozygosity) found in cross-pollinated plants, the focus is often on populations or groups of individuals. Thus, cultivars of cross-pollinated species often are less uniform than those of self-pollinated species. As with self-pollinated crops, mass selection can be used with cross-pollinated crops. One drawback to mass selection in cross-pollinated crops is that there is no guarantee that plants with superior phenotypes will also have superior genotypes. A better approach for cross-pollinated plants is hybridization.

Hybridization

The process of hybridization is commonly used in breeding cross-pollinated species. A **hybrid** is the offspring that results from the hybridization process. We discuss the production of hybrids using corn as an example. Corn has separate male and female flowers on the same plant (monoecious). Creating corn hybrids

involves control of the pollen flow among plants. Production of corn hybrids has the following steps:

1. Development of corn **inbreds** by self-pollinating selected corn plants for several generations to make a uniform variety. Inbreeding often results in loss of vigor. With corn inbreeding, this is accomplished by bagging (with a paper bag) the tassel, collecting the pollen, and then transferring the pollen to the silks of the same plant. These inbreds are carefully evaluated each year and selected for desirable traits. Inbreeding creates a homozygous genetic situation in the plant. It is easier to control genetic transmission this way. In naturally self-pollinated species, the inbreeding step can be skipped because these plants are generally homozygous.
2. The actual corn hybrid is produced by crossing two inbred plants with distinct genetic traits; one plant is used as the male and the other is used as the female (Figure 9-10). This first hybrid produced, an F_1 hybrid, typically has traits superior to those of either inbred parent. This superior ability is called **hybrid vigor**, or **heterosis**. In commercial seed production, two F_1 hybrids can also be crossed to produce double hybrids. However, most corn hybrids that producers use are F_1 hybrids.

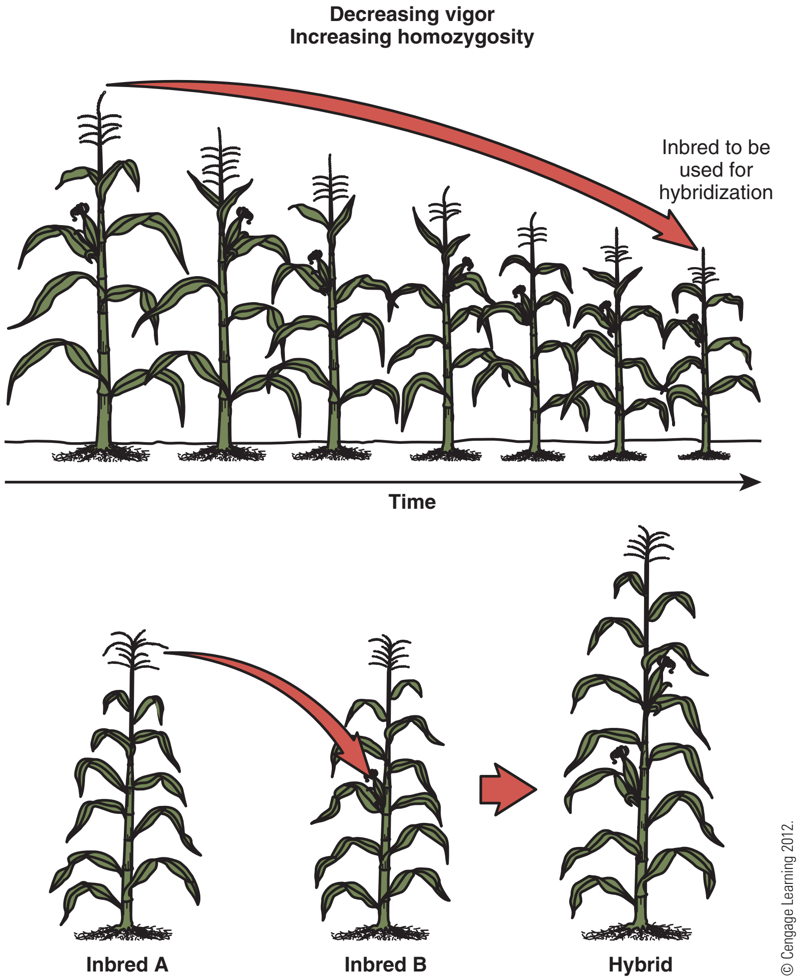


FIGURE 9-10 Hybrid corn production. The first step in developing hybrid corn is producing the inbred line (top). Plants are self-pollinated to become more uniform in certain traits, which also results in loss of vigor. Hybrid corn is produced by crossing two inbred lines, resulting in offspring that are superior to the parents (bottom).

Hybrid Corn

Before hybrid corn, commercial corn was open-pollinated (i.e., naturally cross-pollinated). Pollen produced in the tassel spread to adjacent plants in the same or neighboring fields. Considerable uncontrolled genetic mixing occurred. Commercial seed with desirable traits was selected from the harvested crop by seedsmen. Some of the many popular open-pollinated corn varieties were 'Reid Yellow Dent,' 'Minnesota 13,' 'Lancaster Sure Crop,' and 'Iodent.' Despite the best efforts of early plant breeders, yield improvement potential was limited because of high levels of gene mixing from high- and low-yielding plants within a field.

Hybrid corn has been viewed by many as one of America's greatest achievements (Crabb, 1992). It has had a significant effect on the quantity and quality of corn that is produced. Corn has been a very important crop throughout the history of the United States, but its economic importance really expanded in the 1900s as a result of the development of hybrid corn. Herbert K. Hayes (1963), one of the pioneers of hybrid corn in the Midwest, showed that within 10 years of hybrid-corn introduction, national corn yield had increased 16 percent (Table 9-2). When farmers saw these yield advantages, they were quick to adopt hybrid-corn varieties and abandon open-pollinated corn. Within 30 years of its introduction, in 1959, almost 95 percent of the corn acreage was planted to hybrid corn. Today, almost all corn is grown from hybrids. Since hybrids were introduced, plant breeders have continued to improve corn and develop hybrids for maximum productivity in specific regions. Average corn yields for the United States in 2009 were nearly 165 bushels per acre (10,347 kilograms per hectare).

George H. Schull, a faculty member at Princeton University, and Edward M. East, of the Connecticut Agricultural Experiment Station (later also of Harvard University) are credited with independently developing

TABLE 9-2

Yields of oats and corn in the United States after the introduction of corn hybridization. *Corn yields increased dramatically as compared to oats. Hayes (1963).*

Year	Oats: Bushels per acre	Oats: In % of 1929 yields	Corn: Bushels per acre	Corn: In % of 1929 yields	Percentage hybrid corn
1929	28	100	26	100	0
1939	29	98	30	116	22.9
1949	32	107	38	147	78.3
1959	38	129	51	200	94.8

(*Continued*)

and implementing the concepts of hybrid corn production in 1909. They recognized that hybrid production was a two-step process: (1) selected parents needed to be inbred for five to seven generations and (2) selected inbreds could then be crossed to produce a superior hybrid with greater yield potential than either original parent. This first cross of inbreds was called a *single cross hybrid*. Later, David Jones, who along with Herbert K. Hayes worked on a team with East, produced double-cross seed from crossing two single cross hybrids. This development reduced the cost of the seed and made large quantities of seed available to producers. The first commercially grown double cross hybrid was released by the Connecticut Agricultural Experiment Station in 1921 and was called 'Burr-Leaming.' Hayes would later move to Minnesota, in 1915, to develop the first hybrid corn breeding program in the Corn Belt.

A hybrid seed corn industry soon formed to meet farmer demand for seed. The early public plant breeders transferred their knowledge of hybrid production to private industry that developed an effective system of breeding, producing, processing, and distributing hybrid seed. Some of the earliest hybrid seed corn companies were Funk Brothers Seed Company, started in 1923 in Bloomington, Illinois; Pioneer Hi-Bred Corn Company, started in 1920 in Des Moines, Iowa, by Henry A. Wallace (who would later become a vice president of the United States); Pfister Hybrid Corn Company, started in 1933; and Dekalb Plant Genetics, started in 1924. These companies and others that soon followed were based in the Corn Belt that was and is the center of corn production in the United States. Pioneer Hi-Bred International, Inc., now owned by DuPont, is the largest hybrid seed corn company in the world.

The development of hybridization positioned corn as an important crop in the industrialization of American agriculture. Fertilizer, seed production, and pest control industries were built to grow hybrid corn in large quantities. Corn processing and livestock industries developed to use it as a raw material. A crop that was critical for Native Americans' food and ceremonial purposes is now a raw material for plastic, ethanol, and other products used by our society. In 2007, the demand for corn as an ethanol biofuel stimulated the price of corn, and farmers increased production to almost 93 million acres (38 million hectares), the most since World War II.

Genetic Transformation

Plant breeding techniques evolved rapidly over the past 20 years due to several technological advances in the fields of molecular biology and biotechnology. Techniques permitting the isolation and sequencing of genes (i.e., determining their nucleotide sequence composition) and their transfer from one individual to another (from the same or different species), along with techniques allowing for the "visualization" of genotypes are revolutionizing breeding programs.

The genomes of several plant species have now been sequenced (e.g., *Arabidopsis thaliana* and rice), meaning that the entire nucleotide sequence of these plants is known. This knowledge, when combined with the use of computer-based systems to analyze biological data, provides the foundation for future crop improvement, because it provides information on the possible role of genes and their locations on chromosomes. The development of genetic engineering and marker-assisted selection are two of the most important recent technological advances.

Genetic Engineering

Genetic engineering uses gene transformation or recombinant DNA technology to enable the transfer of one or several genes of interest into a plant with otherwise desirable characteristics. This technique is similar to some aspects of conventional breeding. However, the key difference is that the gene may originate from a wide range of sources, including non-plant sources (e.g., from bacteria, animals, or viruses). Organisms generated using this technique are known as **transgenic**, **genetically modified organisms (GMOs)**, or **genetically engineered organisms (GEOs)**. This approach has been used to select for qualitative traits to develop herbicide- and disease-resistant cultivars. Examples include soybean and corn resistant to the broad-spectrum herbicide glyphosate, and papaya and cassava cultivars resistant to economically important viruses (Table 9-3).

Gene transfer is achieved mainly via the use of a bacterium (*Agrobacterium tumefaciens*), or an instrument known as a *gene gun* (Figure 9-11). Plant transformation involves using ***Agrobacterium tumefaciens***, a pathogenic soil bacterium, to transfer DNA from a plasmid it contains. A plasmid is a circular, independent, non-chromosomal strand of DNA found in some bacteria. The plasmid of *Agrobacterium tumefaciens* naturally contains genes that integrate DNA elements in plant genomes. For the purpose of transformation, some of the original genes in the plasmid have been removed and replaced with the gene of interest and a selectable marker gene. The transformation is accomplished by putting *Agrobacterium tumefaciens* containing the modified plasmid in contact with plant cells. The plasmid transfers part of its DNA to the plant cell, which becomes integrated into the plant's genome. The selectable marker gene has a trait such as antibiotic resistance that permits the identification of the few cells that have been successfully transformed. These are later regenerated using tissue-culture techniques that allow for the regeneration of entire plants from single cells.

In contrast, the gene gun is used to insert the gene of interest by shooting coated gold or tungsten micro-particles into plant cells. A portion of the cells shot will integrate the gene of interest into their genome. These will be, as mentioned before, regenerated into whole plants using tissue culture.

Genetically modified crops now represent a large proportion of the acreage of many major crops grown in the United States including soybean, cotton, corn, and canola. For example, in 2010, more than 91 percent of the acreage of soybeans, 88 percent of cotton, and 85 percent of corn in the United States was planted with transgenic cultivars. The prevalent trait in genetically modified corn, soybean, cotton, and canola is tolerance to the herbicide glyphosate. This allows for relatively inexpensive and efficient weed control. In addition, considerable acreage

TABLE 9-3

Examples of transgenic plants in North America (unless otherwise mentioned).
Agbios database (2007).

Species	Trait inserted	Origin of the inserted gene or nucleotide sequence	Year of governmental approval
Canola	Resistance to the herbicide glyphosate	*Agrobacterium tumefaciens* and *Ochrobactrum anthropi* (bacteria)	1994
Canola	Modified seed fatty acid content	*Umbellularia californica* (tree)	1994
Soybean	Resistance to the herbicide glyphosate	*Agrobacterium tumefaciens*	1994
Corn	Resistance to the herbicide glyphosate	*Agrobacterium tumefaciens*	1996
Corn	Resistance to the European corn borer (production of the protein Cry1Ab)	*Bacillus thuringiensis* (bacteria)	1996
Potato	Resistance to Colorado potato beetle (production of the protein Cry3A)	*Bacillus thuringiensis*	1996
Tomato	Delayed ripening by introduction of a gene that results in degradation of a precursor of ethylene (a plant hormone)	*Escherichia coli* (bacteria)	1996
Papaya	Resistance to infection by the papaya ringspot virus	Papaya ringspot virus	1997
Carnation	Modified flower color	Petunia and viola (plants)	1998 (in Europe only)
Sugar beet	Resistance to the herbicide glyphosate	*Agrobacterium tumefaciens*	1998
Tobacco	Reduced nicotine content	Tobacco	2002
Wheat	Resistance to the herbicide glyphosate	*Agrobacterium tumefaciens*	2004
Alfalfa	Resistance to the herbicide glyphosate	*Agrobacterium tumefaciens*	2004
Rice	Phosphinothricin herbicide tolerance	*Streptomyces*	2006
Plum	Resistance to plum pox virus	Plum pox virus	2007

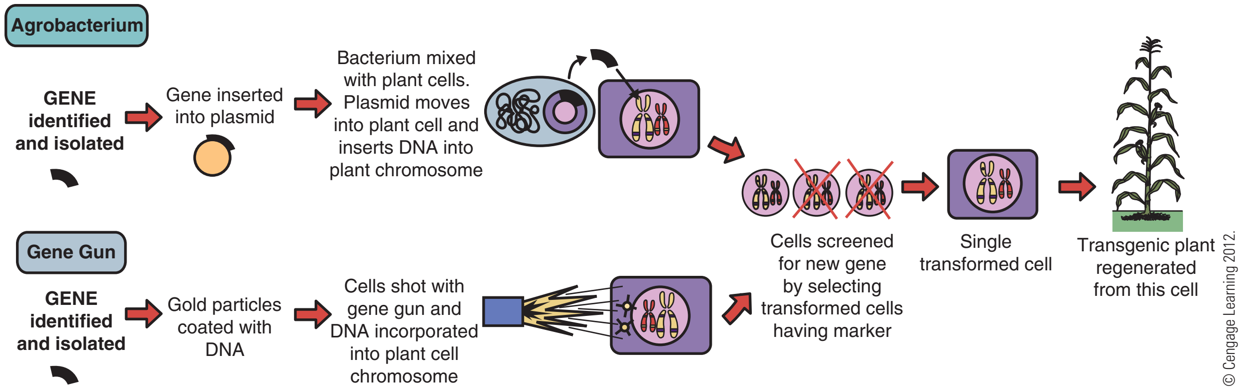


FIGURE 9-11 Genetic engineering of plants by using *Agrobacterium tumefaciens* or a gene gun.

of genetically modified herbicide-tolerant corn and cotton also has traits for resistance to insect pests.

A crop with more than one transgenic trait is called a **stacked-trait** variety. For instance, it is very common to have herbicide resistance and insect resistance in a single variety. A corn variety can be triple stacked (with three traits), quad stacked (with four traits), and new varieties are being developed that have eight or more stacked traits. Triple-stacked corn contains genes for glyphosate, corn borer, and root worm resistance, which offers farmers multiple levels of protection against pests. Stacked varieties can be achieved by inserting each gene separately through genetic engineering or by crossing transgenic crops with different traits using traditional breeding methods.

Genetically Modified Plants: Friends or Foes?

The development of genetic engineering is probably one of the most important advances in the area of plant improvement in recent years. It is also one of the most contentious topics. Some see genetic transformation as a powerful tool to improve crops, whereas others see it as a threat to the environment and human health.

Potential benefits of genetic engineering include the ability to introduce traits in crops such as the following:

1. Biological resistance to pests and diseases eliminates the need for application of insecticides that have a negative impact on the environment (e.g., *Bt* corn provides resistance to the European corn borer, a problematic pest in many regions).
2. Tolerance to herbicides has reduced the quantity of herbicides applied to some crops (e.g., Roundup Ready crops are tolerant to the nonselective herbicide glyphosate, which has limited persistence in the environment and has shown little demonstrated impact on the environment). The use of the Roundup Ready technology has also promoted conservation tillage practices because Round-Up can be applied multiple times to the crop after it emerges.

3. Adaptation to environmental stresses (e.g., resistance to high soil salt levels).
4. Desirable functional characteristics (e.g., tomatoes that have a longer shelf life).
5. Desirable nutritional characteristics (e.g., Golden rice has a high concentration of beta-carotene in its grain).

However, the development of transgenic plants also has raised some concerns, including:

1. Overall safety of genetically modified plants and genetic engineering
2. Impact on human health, because we do not know the long-term impact of consuming food produced from transgenic plants
3. Ability for genetically engineered plants to outcross with weedy relatives or the possibility that they themselves might become difficult to control
4. Unintended effects on nontarget organisms (e.g., a possible negative effect on beneficial insects of some proteins introduced in plants such as those in *Bt* corn)
5. The development of insects and weeds that are resistant to *Bt* or glyphosate, respectively, resulting from overuse of the technology
6. Ethical and religious issues related to genetic engineering and ownership of genes introduced in genetically modified plants. There is often a technology fee for transgenic seeds, which often makes them more expensive than nontransgenic seeds. Also, it is illegal to reuse seeds from harvested, genetically engineered crops, meaning that the following year, farmers cannot reuse seeds harvested from their transgenic crop fields.

One of the best examples of the contentious nature of transgenic plants is the development of Golden rice. Golden rice was developed in 2000 through genetic engineering. It has the unique ability to synthesize and accumulate large quantities of beta-carotene in its grain. This is a significant development because beta-carotene is the precursor of Vitamin A. Vitamin A deficiency in developing countries often leads to irreversible blindness and death. It was hoped that Golden rice could provide better nutrition for malnourished people. However, despite its great potential, Golden rice has yet not been used on a large scale. It has met significant opposition from some environmental groups that contend its safety remains to be evaluated in nutritional trials and the widespread use of Golden rice could threaten rice biodiversity.

In the United States, farmers have adopted transgenic corn, cotton, and soybean to potentially increase profit by increasing yields through improved pest control. They also aim to increase the efficiency of crop production by reducing management and labor costs. Acceptance of genetically modified plants varies between regions and communities, their use being widespread in North America and limited in Europe and Japan, where people have asked for and received policies to limit their use and to label food derived from transgenic plants.

Marker-Based Selection

Molecular markers are DNA segments that facilitate the selection of useful traits and alleles during the breeding process. These markers can be seen once the DNA is isolated from plant samples. Molecular markers are particularly useful for



Roundup Ready Alfalfa and the Supreme Court

Roundup Ready alfalfa was developed by a partnership of Monsanto, a leading plant genetics company, and Forage Genetics International, an alfalfa-breeding company. Roundup Ready alfalfa has been genetically engineered to contain genes for tolerance to the nonselective herbicide glyphosate, the active ingredient in Roundup herbicide. Roundup herbicide can be applied to stands of the crops to control many annual and perennial weeds. Roundup Ready corn hybrids and soybean varieties are currently planted on many acres in the United States.

Roundup Ready alfalfa was first released commercially in 2005. However, in 2007, the Center for Food Safety, along with several other nonprofit organizations and alfalfa growers, sued the USDA claiming the agency's decision to allow farmer planting of Roundup-tolerant alfalfa violated the National Environmental Policy Act (NEPA). The subsequent ruling by the Federal District Court in California stated that the USDA Animal and Plant Health Inspection Service (APHIS) prematurely allowed the sale and cultivation of Roundup Ready alfalfa. The court ruled that the Environmental Impact Statement (EIS) should have addressed a range of issues, including the risk that conventional and organic alfalfa will be contaminated by the Roundup Ready gene by pollen flow, and the risk that Roundup Ready alfalfa's use will lead to the development of glyphosate-resistant weeds. In June 2010, the U.S. Supreme Court reversed the lower court's ban on the sale and cultivation of Roundup Ready alfalfa. In 2011, the USDA completed the EIS and gave final approval to the marketing and planting of Roundup Ready alfalfa.

This case demonstrates the complicated nature of development and release of genetically engineered crops. Research on development of Roundup Ready alfalfa actually began in the late 1990s, and Monsanto and Forage Genetics International conducted extensive environmental research and submitted documentation to USDA-APHIS before the initial approval by USDA in 2005. It demonstrates USDA-APHIS's function and critical role in approval and regulation of biotech crops while protecting the environment and human health. The case also shows how our judicial system interprets the rules and protects the rights of individuals and organizations who are concerned about environmental issues, as well as those of farmers who choose to grow biotech crops.

quantitative traits because they are associated with regions of the genome that contribute to a specific trait. It is possible to rapidly screen for individuals carrying a desirable characteristic among a large number of individuals or samples. Markers are also useful because they allow for the confirmation of the presence of

specific alleles and can be used to complement or replace phenotypic selection. In addition to permitting the selection of several alleles affecting the same complex trait, molecular markers have several advantages over phenotypic selection. They are faster and more consistent. The use of molecular markers is not limited to transgenic plants; they can aid in conventional breeding programs, too. At this time, marker-assisted selection is used only in breeding programs for a few species.



Breeding Perennial Grain Crops

Perennial crops that live for many years can hold soil even when otherwise it would be washed downhill or blown away. Many perennials build soil organic matter, improving the quality of the soil. Deep perennial roots present in the soil all year can outcompete weeds and effectively take up a large fraction of applied fertilizers, so they are not lost to ground or surface waters as pollutants.

Unfortunately, human food security depends directly upon the production of short-lived grain crops—they currently occupy nearly 70 percent of global crop land. These grains are all the familiar crops such as wheat, rice, corn, and soybean. When annual grains are grown on marginal lands, the productivity of the soil can be quickly lost. About half the human population currently depends on food being produced on these fragile lands. Clearly, food security depends on methods to sustainably produce abundant food from these challenging landscapes.

One solution is to develop perennial crops that yield grain. Grains are nutrient-rich, and are easily harvested, stored, transported, and processed into a wide variety of desirable foods. When these features are paired with the ability to live for many years, the combination will both feed people and hold the soil.

The idea of developing perennial grain crops is not new, but recently expanded efforts with numerous crops only began since the year 2000. Good progress has been made with perennial sorghum, wheat, sunflower, rye, and rice. These crops all have perennial relatives with which they can be intermated. Genetic difficulties often result when different species are crossed, but these problems can be addressed through traditional breeding and molecular marker strategies.

Another approach is to start with promising wild perennial plants and domesticate them. With this method, the difficulties of wide crosses are avoided, but there is the added challenge of introducing a new crop into the human diet. Although many perennial plants have low seed yield and small seed size, they often possess large genetic variability for these traits (Figure 9-12). Therefore, breeding progress can be rapid. For example, scientists at the Land Institute have more than doubled seed size in one perennial grass in seven years.

(*Continued*)

Perennial grains will continue to require time for development, even with the application of modern genetic tools. However, scientists at the Land Institute are optimistic that the first perennial grain crops will be grown profitably in farmers' fields within a decade or two. Perennial grains will be able to turn profit at lower yields than annuals due to reduced input costs, so their adoption should be rapid once the genetic problems are worked out.

Lee DeHaan. <http://www.landinstitute.org/> (The Land Institute is a nonprofit agricultural research organization.)

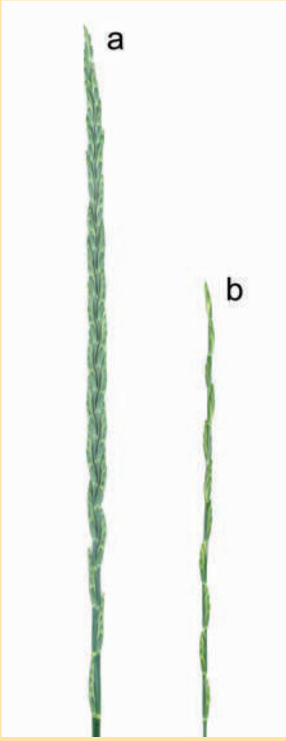


FIGURE 9-12 Head from an intermediate wheatgrass (*Thinopyrum intermedium*) plant developed through four cycles of selection as a perennial grain (a), compared to the head of a wild, unselected plant (b). Dramatic changes in grain and inflorescence size such as these are not uncommon in perennial grain domestication programs, and hold promise for potential breakthroughs in yield.

Lee DeHaan, The Land Institute.

Traditional Breeding versus Genetic Engineering

The availability of molecular techniques enables the insertion of desirable genes and alleles into crops at a much faster rate and degree of precision than classical breeding methods (Figure 9-13). Therefore, they enable a quicker release of superior cultivars onto the market. Molecular biology and biotechnology are now, along with classical hybridization and selection methods, an important component of many breeding programs. However, traditional breeding techniques will still be used in the future. Organic agriculture, for instance, prohibits the use of genetically engineered products. Many foreign export markets also demand nontransgenic products.

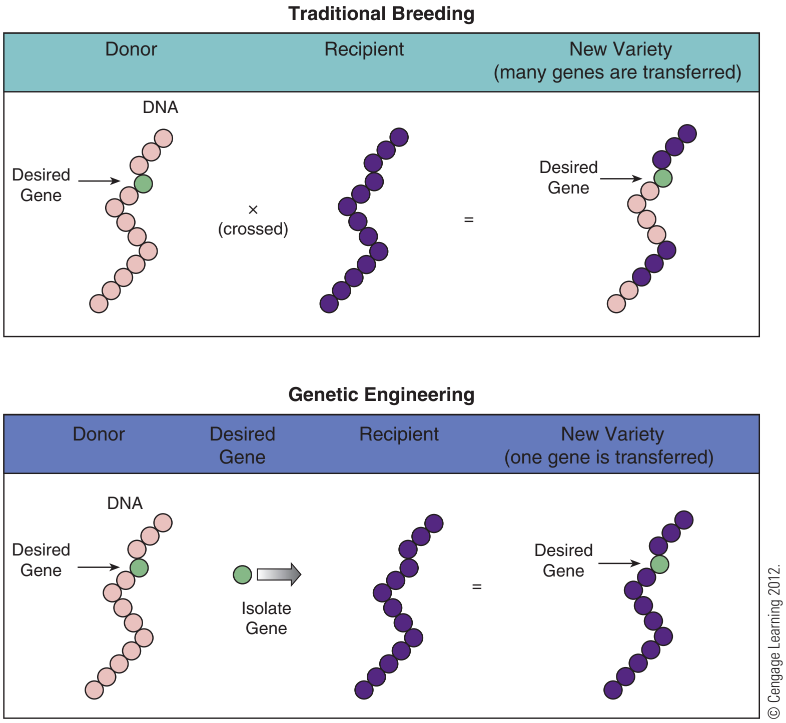


FIGURE 9-13 Traditional breeding versus genetic engineering. In traditional breeding, many genes are combined. In genetic engineering, just one gene may be transferred.

Breeding and Marketing Modern Crop Varieties

Varieties of most widely grown or high-value crops like corn, soybean, cotton, alfalfa, sugar beets, wheat, and rice are produced by breeders working for large, private companies. These companies typically engage in competitive marketing of their varieties and hybrids. However, varieties of some commodity crops like food-type soybean, edible beans, barley, oat, and wheat, as well as forage crops like clovers and perennial grasses, are produced by breeders at land-grant universities. Marketing of these publicly produced varieties most often occurs through agreements with private seed companies.

Most modern varieties are patented by plant breeders, public institutions, or the private companies that develop them. The patenting process was established for asexually propagated crops like apples and Bermuda grass by the Plant Patent Act of 1930, and for sexually propagated crops like corn and soybean by the Plant Variety Protection Act of 1970. Varieties with traits produced by genetic engineering are protected by other types of patents and trademarks.

As for any other invention, patenting of varieties protects the intellectual property rights and investments of those who develop them. Patenting also ensures varietal trait purity by controlling the production and sale of seed. Use of a patented variety by a grower often provides monetary return to the developer in the forms of royalties or fees. Royalties from the sales of seed of plant varieties are used to support crop breeding programs and for private companies to provide a return on their investment.

Until the 1950s, publicly supported land-grant universities and the United States Department of Agriculture conducted most of the crop breeding programs. The improved crop varieties these programs released were considered public property, and farmers often saved their own seed for producing the next crop. Farmers with excess seed sometimes sold some to other farmers for planting. Today, "brown-bagging" sales (a term to describe packaging in a nondescript brown bag) by farmers of a seed that is patent protected is considered "seed piracy" and is illegal. In addition, for most varieties with patented traits developed through genetic engineering, farmers are not allowed to save any seed for replanting or sales.

Review Questions

1. Describe the terms *self*- and *cross-pollinated crops* and list examples for each.
2. Identify differences between mitosis and meiosis.
3. Explain how qualitative and quantitative traits differ.
4. What are the laws of inheritance?
5. Show the genotypes of progeny resulting from the cross of two plants that are heterozygous for the same trait.
6. Where can the largest diversity for a given crop be found?
7. Briefly describe the steps involved in the development of a new corn hybrid.
8. Explain how genetically modified organisms are generated.
9. List some of the traits that have been introduced in genetically modified crops.
10. What are some concerns about using transgenic plants?

Critical Thinking

1. Review the specific yield or quality changes resulting from plant breeding in important crops such as cotton, sugar beet, alfalfa, and others that are adapted to your region.
2. You have discovered a new plant species. How could you easily determine if this species is self- or cross-pollinated?
3. Genetic engineering is said by some to be more efficient than traditional plant breeding. Why?
4. Do you support the use of transgenic plants in agriculture? Why or why not?
5. Do you think that molecular breeding will replace traditional breeding methods in the near future? Why or why not?
6. Investigate and discuss the role of Seed Savers Exchange or the Svalbard Global Seed Vault in preserving crop genetic resources.

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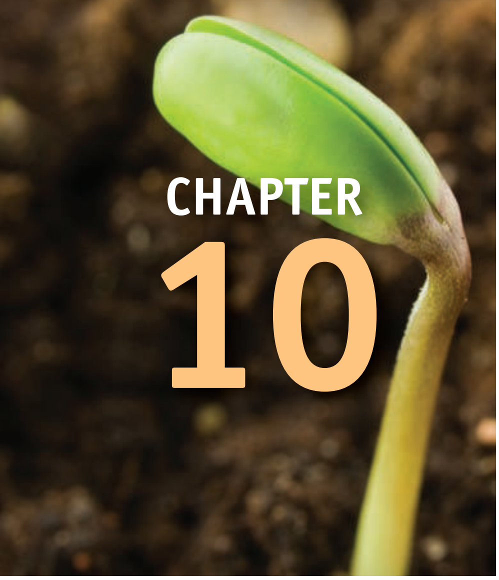
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CHAPTER 10



Environment





Key Concepts

- The sun is the source of all the energy on the earth and is the driving force behind our climates. Quality, duration, and intensity are three components of the sun's energy that influence plant growth.
- The solar energy received on the earth is influenced by latitude, season, and time of day.
- Global warming is associated with an enhancement of the greenhouse effect due to an increase in the concentration of carbon dioxide, methane, and nitrous oxide in the earth's atmosphere.
- Functions of the atmosphere include the source of precipitation and air, protecting the earth from radiation, and moderating the earth's temperature.
- Climate is the typical, long-term (usually 30 years) weather conditions in a region.
- Precipitation and temperature are important features of climate that affect human activities and agricultural practices.
- Crop selection, residue management, fallowing, irrigation, and soil drainage are important management practices related to temperature and precipitation.

Key Terms

air mass
arid region
atmosphere
carbon dioxide (CO_2)
chilling injury
climate
crop insurance
diurnal
dormancy
drainage system
drought
dry climate
El Niño
equator
fall equinox
fallowing
flooding
freezing injury
global warming
greenhouse effect
heat injury
humid region
hydrophytes
irrigation
Koppen system
latitude
light intensity
light quality
longitude
mesophyte
methane (CH_4)
mid-latitude climate
mulch
orographic effect
planting date
precipitation

- season
- semiarid region
- semi-humid region
- spring equinox
- sprinkler irrigation
- stratosphere
- subtropical
- summer solstice
- surface irrigation
- temperate
- temperature
- tropical
- tropical climate
- tropics
- troposphere
- water cycle
- weather
- winter solstice
- xerophyte
- zenith

Introduction

Many aspects of our environment influence crop production practices. The sun is the source of all energy on the earth, and its characteristics influence atmospheric characteristics, photosynthesis, and other plant growth processes. The pattern of the sun's energy distribution on the earth creates **climate** as do topographic features. Temperature and precipitation are two important aspects of climate that influence human activity and crop production. Producers select crops and develop management strategies to make optimum use of their environmental resources.

The Sun's Energy

Life on the earth is dependent on energy from the sun, a burning star that is 93 million miles (150 million kilometers) from the earth. Nuclear reactions convert the sun's mass to energy. Most of the sun's energy is radiated into space, and less than 1 percent of the total energy generated by the sun reaches the earth's surface. Of the portion reaching the earth, only about 50 percent is absorbed by the earth's surface (Figure 10-1). The radiant energy that the sun produces ranges from short-wave cosmic rays to longer radio waves (Figure 10-2). Only a small portion of the sun's energy spectrum is used for vision or plant processes such as photosynthesis. The sun's energy travels in bundles called photons and moves in waves. The energy level of radiant energy is related to wavelength; energy is greatest at the shortest wavelengths and is least at the longest wavelengths.

Seasonal and Day Length Effects

The inclination of the earth, the yearly orbit of the earth around the sun, and the daily spin of the earth interact to cause variation in the amount and quality of the light received on the earth. The amount of solar energy received on the earth's surface influences our spring, summer, fall, and winter seasonal climates in the northern hemisphere of the earth. The **seasons** occur because the earth's north–south axis is always tilted 23.5° from its plane of orbit. During the earth's orbit, the northern hemisphere is inclined toward the sun in the summer and receives more solar energy than the southern hemisphere does (Figure 10-3). In contrast, the northern hemisphere tilts away from the sun in the winter. At the **spring** and **fall equinoxes** (about March 21 and September 21), equal amounts of solar radiation

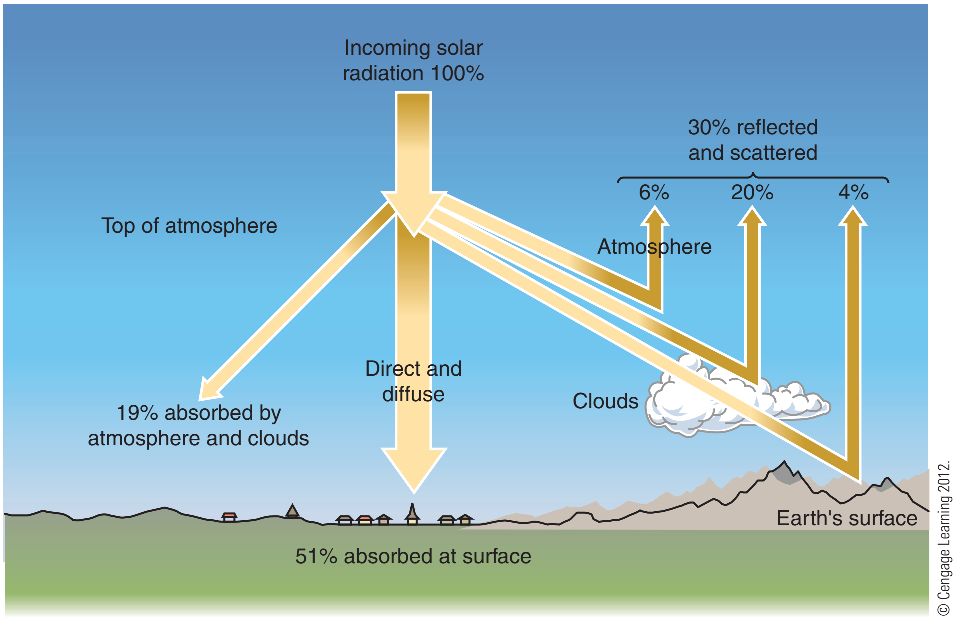


FIGURE 10-1 Only about 50 percent of the sun's energy that reaches the earth's atmosphere is absorbed by the earth's surface. The earth's atmosphere absorbs and reflects a significant portion of the total energy.

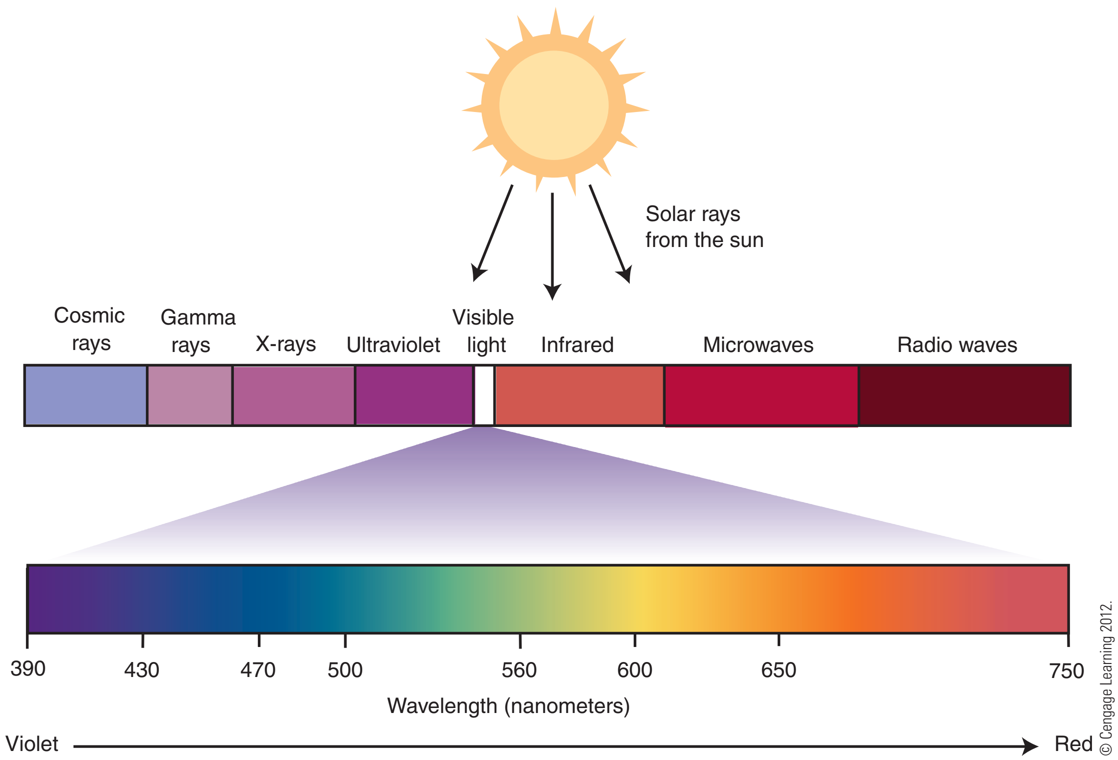


FIGURE 10-2 The radiant energy spectrum generated from the sun.

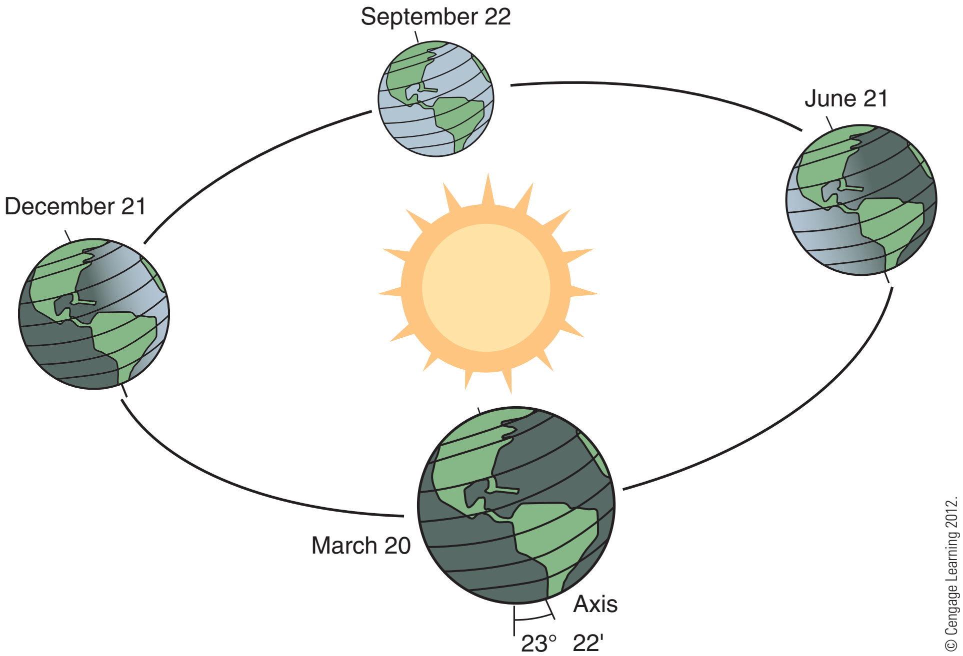


FIGURE 10-3
The position of the earth during its annual movement around the sun. During the winter solstice, the earth is closer to the sun than in the summer, and the northern hemisphere tilts away from the sun. During the summer solstice, the northern hemisphere is inclined toward the sun and receives more solar energy than the southern hemisphere.

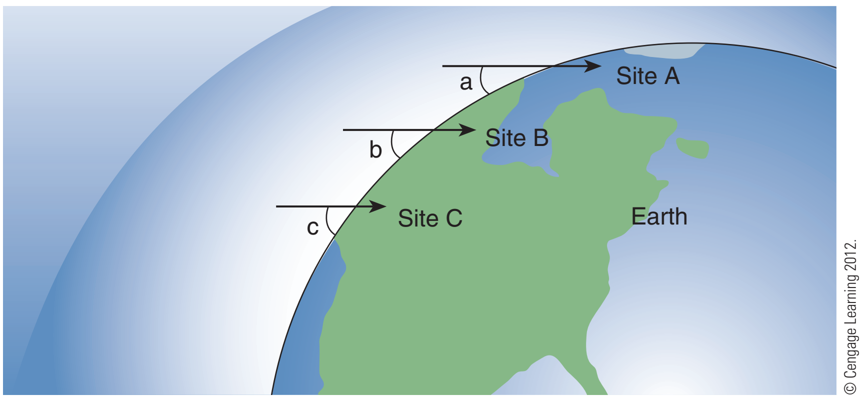


FIGURE 10-4
Angle of sunlight striking the earth with changing latitude. Angle C > Angle B > Angle A. The energy received at site A is more dispersed and is less per unit area than at site C.

reach the northern and southern hemispheres. Warm summer air is present because the days are longer and because the sun is closest to its **zenith** (highest point in the sky), resulting in a greater intensity of energy striking the earth's surface.

The amount of solar radiation received per unit area of the earth's surface is greatly influenced by the angle at which the solar energy is received (Figure 10-4). That angle is affected by the latitude and the season of the year. At the **equator**, the imaginary line circling the earth that is equidistant between the two poles, the sun's radiation strikes the earth at about a 90° angle. As latitude increases in the northern and southern hemispheres, the curvature of the earth changes, and the sun's energy travels further through the atmosphere to reach the earth's surface. The energy is also distributed over a larger surface area than at the equator. Therefore, regions around the equator have a warmer average temperature than do more northern latitudes. There is also a pronounced seasonal effect on the

angle of sunlight in the northern and southern hemispheres. During the winter in the northern hemisphere, the angle of sunlight is reduced compared to the summer. This, in combination with shorter day length, results in lower winter air temperatures than in the summer.

Because of the earth's 24-hour rotation, the sun's radiation is received only between sunrise and sunset. Day length varies with latitude and season of the year. At the equator, day length throughout the year is always 12 hours. However, at latitudes north and south of the equator, equal day and night periods occur only at the spring and fall equinoxes. In northern latitudes, days become shorter until the **winter solstice** on December 21 and are longest at the **summer solstice** on June 21 (Table 10-1). During the day, light intensity is always greatest when the sun comes closest to the zenith. This is called the *solar noon*.

Light Effects on Plants

In describing the effects of light on plants, three properties are important. These are light quality, light duration, and light intensity.

Light Quality

Light quality is described in terms of the wavelength of sunlight. The visible light spectrum has wavelengths of about 400–750 nanometers. Plants mostly use light in the blue and red wavelengths and reflect green wavelengths that are in the middle of the visible spectrum. Chlorophyll, the pigment responsible for light absorption during photosynthesis, absorbs light of varying wavelengths, but it has peak absorptions in the 420–460 nanometer wavelengths and in the 620–680 nanometer wavelengths. Plants are adapted to a specific light quality, and field crop producers can do little to manage this factor. Artificial light in greenhouses and growth chambers must provide light at the proper wavelengths by using the correct lighting system to optimize plant growth.

TABLE 10-1

The effect of latitude on day length at the spring and fall equinoxes (March 21 and September 21) and at the summer and winter solstices (June 21 and December 21).

		March 21	June 21	Sept. 21	Dec. 21
Latitude	Location	hours			
71.18° N	Barrow, AK	12	24.0	12	4.1
61.13° N	Anchorage, AK	12	19.3	12	5.4
45.00° N	St. Paul, MN	12	15.6	12	8.8
40.00° N	Columbus, OH	12	15.0	12	9.3
30.16° N	Austin, TX	12	14.1	12	10.2
18.30° N	San Juan, PR	12	13.2	12	11.0
8.58° N	Panama City, Panama	12	12.6	12	11.6
0.13° S	Quito, Ecuador	12	12.0	12	12.0

Latitude and Longitude

Greek mathematicians around 200 BCE first developed the concepts of **latitude** and **longitude** for mapping the world and to assist in navigation and astronomy. Latitude is a measurement in degrees (°) ranging from 0° at the equator to 90° at the poles (90° N for the north pole and 90° S for the south pole). Each degree of latitude is about 69 miles (111 kilometers). Latitude is divided into minutes (60 minutes/degree) and seconds (60 seconds/minute). Besides the equator, four other lines of latitude are named because of the role they play in the geometrical relationship between the earth and the sun. These are the Arctic Circle (66°33′39″N), the Antarctic Circle (66°33′39″S), the Tropic of Cancer (23°26′21″N), and the Tropic of Capricorn (23°26′21″S). Only at latitudes between the Tropics is it possible for the sun to be at its zenith, or directly above.

Longitude describes the location of a place on the earth that is east or west of a north–south line called the *prime meridian*. It is given as a measurement where 0° is at the prime meridian and then going +180° eastward and −180° westward.

Light Duration

Photoperiodism is a plant's response to changing lengths of day and night. This response involves the pigment phytochrome, which senses changes in the proportion of red (absorption peak at 660 nanometers) and far-red light (absorption peak at 730 nanometers). The physiological basis behind this response is discussed in Chapter 8. Photoperiodism affects several important plant processes. These include flowering and dormancy. Plants can be categorized by their flowering responses to day length: short-day, long-day, or day-neutral.

Temperate perennial plants such as alfalfa and perennial grasses respond to the shortening days in the fall and undergo a **dormancy** reaction. During this reaction, plants divert energy from vegetative production into storage reserves in roots and bulbs. They also form buds that overwinter and resume growth the following spring. Producers can use their knowledge of the dormancy reaction to select varieties with a dormancy reaction that provides for adequate winter hardiness in their region.

Light Intensity

Light intensity refers to the quantity or brightness of light. It is expressed as uE $m^{-2}s^{-1}$. Light intensity is influenced by several factors.

- **Time of day.** Light intensity is always greatest when the sun comes closest to the zenith. As a result, plant photosynthetic productivity displays a **diurnal**, or

daily, variation. It is greatest during the solar noon and lower in the mornings and evenings.

- **Latitude.** The amount of solar radiation reaching the earth's surface is greatest at the equator; it is reduced by latitude because the same amount of radiant energy travels further before reaching the earth's surface and is spread over a wider surface area. The result is that plants originating in tropical areas, for example, corn and sugarcane, contain photosynthetic pathways that are especially effective at high levels of solar radiation (see Chapter 8). Plants from temperate regions, for example, alfalfa and wheat, have different pathways.
- **Seasons.** Because of the variation in day length and angle of solar radiation reaching the earth, the solar energy received varies with the season. Solar energy reception is greatest in the summer and least in the winter.
- **Topography and aspect.** At northern latitudes, south-facing slopes receive greater radiation than north-facing slopes. As a result, plants growing on south-facing slopes may green up earlier in the spring and suffer more heat stress in the summer.

Our Atmosphere

Our **atmosphere** is a gaseous layer extending up to 70 miles (113 kilometers) into space. The earth's atmosphere has four layers: the troposphere, the stratosphere, the mesosphere, and the thermosphere (Figure 10-5). The troposphere and the stratosphere have the greatest impact on our biological activities.

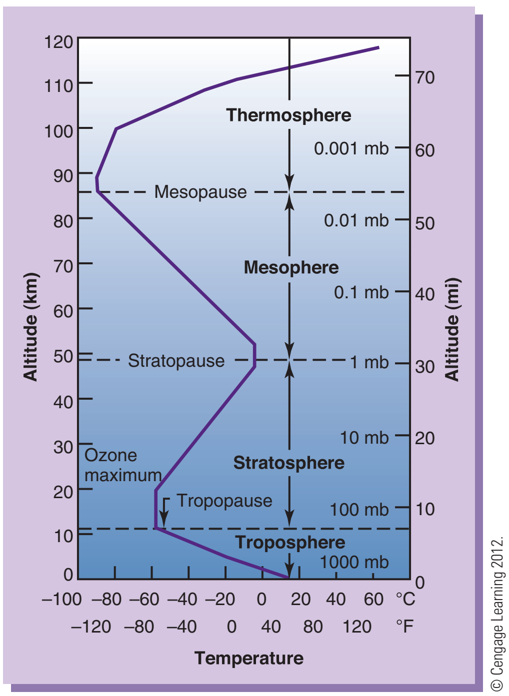


FIGURE 10-5
The layers of the atmosphere, with their temperatures and pressures.

- The **troposphere** is the layer that is closest to the earth's surface. It extends about 8 miles (13 kilometers) into space. It has the greatest concentration of the gases essential for plant and human life and also is the zone where our weather and climate occur (Table 10-2).
- The **stratosphere** extends from 8 to about 30 miles (13–48 kilometers) into space. The stratosphere contains the ozone (O_3) layer. The ozone layer is particularly noted for absorption of the sun's ultraviolet radiation, which is harmful to humans and plants. Thinning of the ozone layer by chlorofluorocarbons (CFCs) used as refrigerants and aerosols has been identified as a significant environmental and human health risk.

Functions of the Atmosphere

The atmosphere has several important functions including the following:

- Source of water vapor that falls as precipitation, carbon dioxide for photosynthesis, oxygen for respiration, and nitrogen for plant growth
- Protection of the earth's surface from harmful energy from the sun. Atmospheric gases such as ozone, carbon dioxide, water vapor, methane, and nitrous oxide absorb ultraviolet radiation.
- Allows selective passage of radiation essential for our vision and for plant processes
- Keeps the earth's temperature at a level at which plants, animals, and other organisms can survive and be productive. This occurs because water vapor, carbon dioxide, methane, and nitrous oxide in the earth's atmosphere absorb radiation that is emitted from the earth's surface and radiate the energy back to the earth's surface. Without our atmosphere, the earth's average surface temperature would be about 10°C lower, and the earth would be uninhabitable.

TABLE 10-2

The permanent and variable gases that make up the earth's atmosphere, and their composition.

Permanent gases			Variable gases		
Gas	Symbol	Percentage (by volume) dry air	Gas (and particles)	Symbol	Percentage (by volume)
Nitrogen	N_2	78.08	Water vapor	H_2O	0 to 4
Oxygen	O_2	20.95	Carbon dioxide	CO_2	0.035*
Argon	Ar	0.93	Methane	CH_4	0.00017
Neon	Ne	0.0018	Nitrous oxide	N_2O	0.00003
Helium	He	0.0005	Ozone	O_3	0.000004
Hydrogen	N_2	0.00006	Particles (dust, soot, etc.)		0.000001
Xenon	Xe	0.000009	Chlorofluorocarbons	CFCs	0.00000001

*For CO_2, 0.035 percent is 355 molecules of CO_2 per every million molecules.

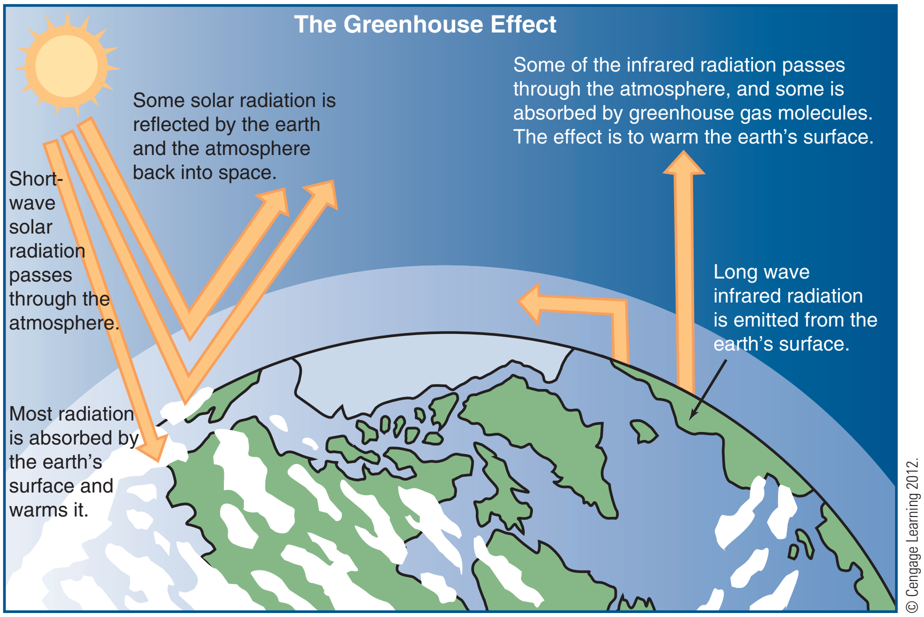


FIGURE 10-6
The greenhouse effect is essential for maintaining the earth's temperature at levels suitable for habitation. The sun's energy passes through the earth's atmosphere and is absorbed by the earth's surface. A portion of that energy is radiated from the earth's surface and is re-radiated by the atmosphere. Global warming may be caused by the increase in greenhouse gasses such as carbon dioxide and methane.

The atmosphere acts like greenhouse glass providing insulation and warmth for the earth's surface; this phenomenon is called the **greenhouse effect** (Figure 10-6). The gases involved are called *greenhouse gases*.

Too Much of a Good Thing? Global Warming

Concurrent with the dramatic increases in the earth's population and the industrialization of civilization during the past 100 years, the earth's average air temperature has increased by about 1°F (0.6°C). This is called **global warming**. Global warming may be intensifying the greenhouse effect of the earth's atmosphere through dramatic increases in concentrations of greenhouse gases, especially **carbon dioxide (CO_2)**. Carbon dioxide concentrations in the atmosphere have increased about 20 percent over the past 100 years and are projected to continue to increase (Figure 10-7). The increased carbon dioxide concentration is related to an imbalance in the carbon cycle due to human activity. This activity includes excessive use of fossil fuels in automobiles, manufacturing, agriculture, and heating; deforestation of deciduous and tropical rain forests; and tillage of agricultural lands. Other greenhouse gases related to agriculture include **methane (CH_4)** (Figure 10-8) and nitrous oxide (N_2O). Methane is produced in fermentation reactions by ruminants like cattle, in manure-holding areas, and in wetlands. The process of denitrification produces nitrous oxide from the nitrate in wet soils and wetlands.

If current trends continue, by the end of this century (2099) average air temperatures are projected to increase by several degrees, depending on the increase in levels of greenhouse gases. While a few degrees may not seem like much, such increases in air temperature may cause changes in the earth's biomes; changes in crop-production regions; and increases in extreme weather such as drought, thunderstorms, and hurricanes. Some scientists project that sea levels will rise from 1 to 2 feet (0.3 to 0.6 meter), which could impact low-lying cities such as

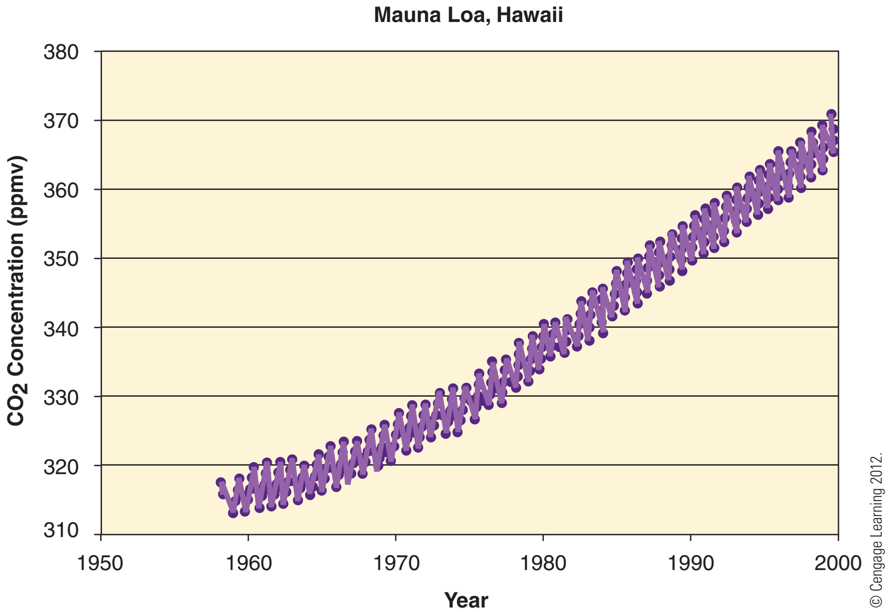


FIGURE 10-7
Changes in atmospheric carbon dioxide levels in parts per million by volume since 1960. The variation around the line is associated with seasonal fluctuations in carbon dioxide levels.

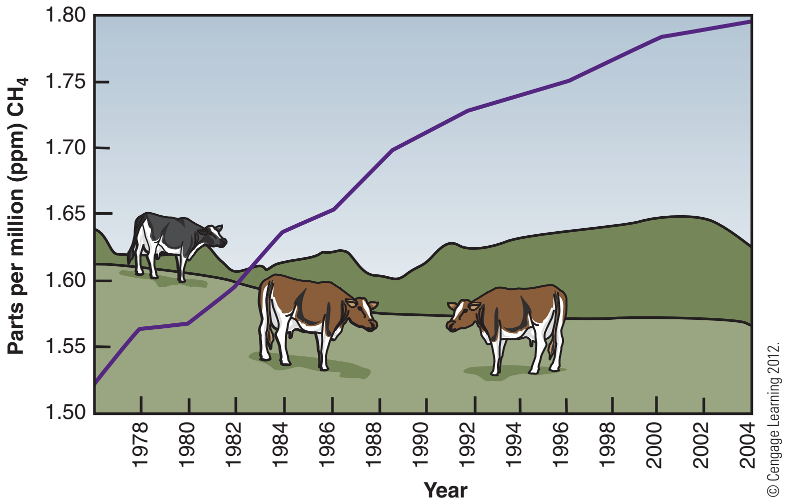


FIGURE 10-8
The atmospheric concentration of methane, another greenhouse gas, has also increased. Methane is produced by ruminant animals and wetlands.

New Orleans, New York, Boston, and Miami. Warmer air temperatures have already been associated with the melting of the polar ice caps and glaciers, reducing the habitat for many animals like polar bears, seals, and penguins.

Whether these predictions will come to pass is still a source of contention. Some do not believe climate change is happening, while others think that even if the climate is changing, it is a natural event and not due to human activity. However, the majority of climate scientists are in accord that global warming is a real occurrence and that people throughout the world need to act to slow global warming. There is an opportunity to moderate global warming by changing human activities and adopting new practices. Potential solutions to reduce carbon dioxide in the atmosphere include reduction in fossil-fuel usage by developing nations and using renewable

fuels such as ethanol, halting deforestation of the tropical rain forests, increasing reforestation of agricultural landscapes, and increasing carbon sequestration of the soil through reduced or minimal tillage. Practices that minimize nitrogen-fertilizer movement into surface waters can decrease nitrous-oxide movement into the air.

Climates of North America

Climate is defined as the typical long-term (usually 30 years) weather conditions in a region. In contrast, **weather** as described daily on TV and radio deals with short-term conditions. We recognize that the climate of the earth changes over time. For example, as noted previously, it appears that we may be in the process of global climate change due to global warming. There are many types of climates in the world. Climate is a product of several factors, including:

- **Solar energy.** The uneven distribution of solar energy on the earth has a huge effect on climate. Incoming radiation is greatest around the tropics and decreases with latitude toward the poles. The transfer of energy from the tropics creates winds and ocean currents that move warm air and energy to the poles and cold air and water toward the equator.
- **Bodies of water.** Lake-effect snows occur because of the contrast in temperature of cold air and relatively warmer water of lakes. The cold air takes up moisture from the water and forms clouds or fog. Ultimately, the moisture is precipitated as snow on land.
- Large bodies of water such as oceans buffer against change in air temperature and cause adjacent land temperatures to vary less from season to season. Consequently, the yearly fluctuations in soil and air temperatures in Minnesota are normally greater than those in New Jersey.
- Interactions of ocean currents and trade winds (strong easterly winds that blow through the tropics and subtropics) create a condition known as **El Niño** along the Pacific coast of South America near the equator. During El Niño, the normal east to west ocean circulation patterns are altered, and warmer ocean water is moved to the Pacific coast of South America and California. The resulting alteration in the jet stream results in warmer and drier winters for the northern third of the United States and very wet conditions for the southern United States.
- **Land forms.** Mountains in the path of a moist air mass create uplift of the air. The move to higher elevations causes cooling of the air and cloud formation, creating wet conditions on the windward side and dry conditions on the leeward side as the air descends. This is called an **orographic effect** (Figure 10-9). As moist Pacific air encounters the Rocky Mountains, rain and snow are deposited on the windward side of the mountains while semiarid and desert conditions occur on the leeward side. On the leeward side of mountains, low-pressure regions that affect regional weather can also be created.
- **Elevation.** Elevation changes due to mountains and other landforms affect air temperature. For each 300-foot (91 meters) increase in elevation, average temperatures decline about 18°F (10°C). Higher elevation decreases temperature because atmospheric gases are less concentrated and radiant heat loss is greater.

- Air masses. **Air masses** are large bodies of air with similar temperature and moisture content. The climate of North America is greatly affected by several air masses (Figure 10-10).

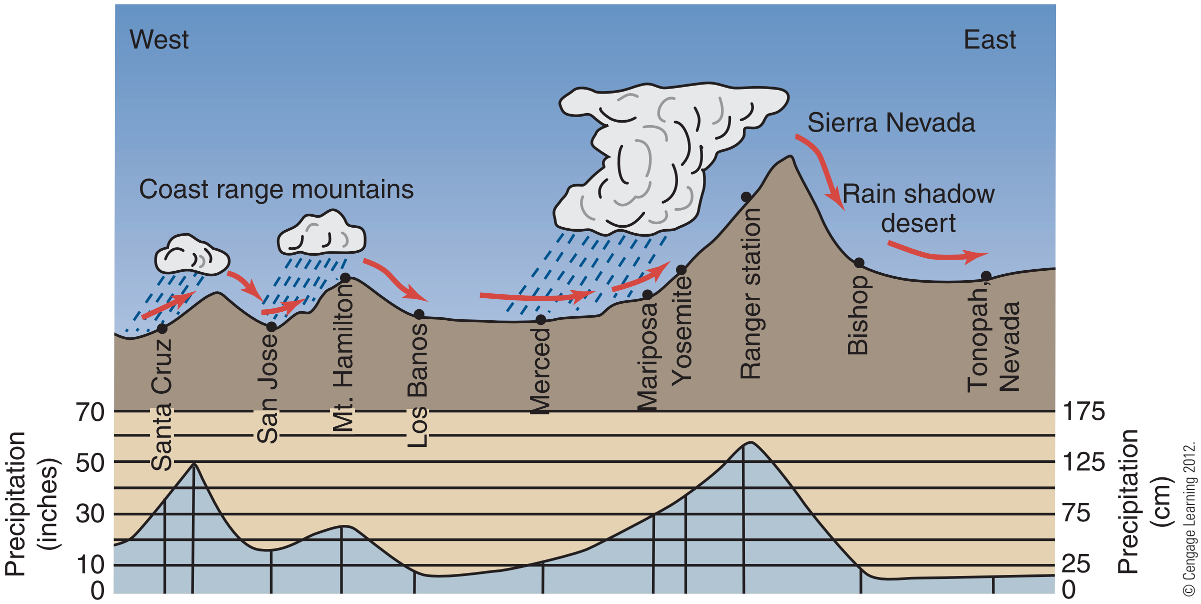


FIGURE 10-9 The orographic effect of mountain regions. The windward side of the mountains is cooler and wetter than the downwind or leeward side of the mountain.



FIGURE 10-10 Air masses affecting North America and their paths of movement. cP is continental polar and cold and dry; cT is continental tropical and hot and dry; mP is maritime pacific and cool and moist, and mT is maritime tropical and warm and moist.

- Continental polar air masses (cP) enter Canada and the United States from northern Canada and Alaska. This air is very cold and contains little moisture. It can penetrate to the eastern United States and the Gulf of Mexico.
- Maritime polar air masses (mP) originate over the northern parts of the Atlantic and Pacific Oceans. The air masses are modified by the ocean water and become warmer and moist.
- Maritime tropical air masses (mT) are warm and moist. The Pacific air mass affects the southern Pacific coast, bringing significant winter precipitation. The Gulf and Atlantic air masses affect the Gulf and Atlantic coasts and also impact climate in all states east of the Rockies.
- Continental tropical air masses (cT) are hot and dry. They occur during the summer in northern Mexico and the southwestern United States.

Climate Classification

The aforementioned climate factors interact to produce unique climates throughout the world. To explain climates and their impact on human civilizations and agriculture, classification systems have been developed. We start with the oldest classification system, developed by the ancient Greeks, and follow with a modern system.

The Greek Classification System

The earliest system for describing the climate was proposed by the Greek philosopher Aristotle. The system was based mostly on his limited knowledge of the effect of latitude on human activity and plant growth. The system was very simple and identified three zones (Figure 10-11). This classification, while too general for modern use, is the basis of several climate-related terms we use today.

- **Torrid or tropical zone.** The **tropics** are the region of the earth centered on the equator. They are bounded by the Tropic of Cancer in the northern hemisphere (23.5° N latitude), and the Tropic of Capricorn in the southern hemisphere (23.5° S latitude). The Tropics of Cancer and Capricorn are the farthest northern and southern latitudes, respectively, at which the sun can appear

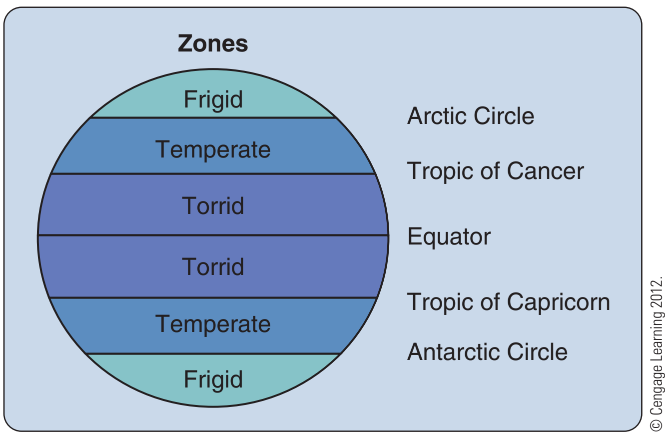


FIGURE 10-11 Climatic zones established by the Greeks.

directly overhead. At the equator, days and nights are of equal length. The ancient Greeks thought this region to be nearly inhabitable due to the heat. In the western hemisphere, we often associate the tropics with the warm and wet conditions of the rain forests of Brazil and Costa Rica, but this region also contains the high and dry mountain ranges of the Andes.

- **Frigid or polar zone.** These regions are either north of the Arctic Circle (66°33'38" N) or south of the Antarctic Circle (66°33'38" S). The polar zones experience extremely low winter temperatures combined with many days of nearly total darkness. Annually, they experience at least one 24-hour period of total daylight (summer solstice).
- **Temperate zone.** The **temperate** zone lies between the tropics and the polar circles. The temperate regions have distinct winter and summer seasons. Much of the United States and Europe is in this zone. Aristotle viewed this as the only habitable region.

The Koppen System

A Russian-German climatologist, Wladimir Koppen, developed a system called the **Koppen system** in the early 1900s. It divides the earth into climatic regions based on temperature and precipitation. The system has some of the designations used in the Greek system, but it identifies five major climate types as well as subclimates (Figure 10-12). These climates affect the native vegetation in the regions as well as many current cropping practices.

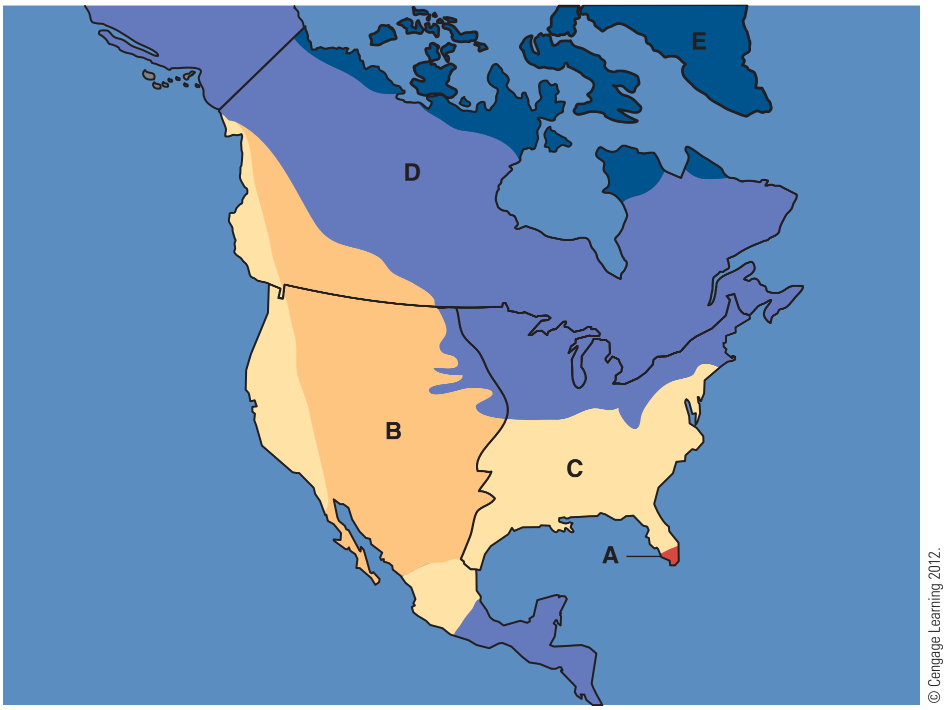


FIGURE 10-12 Distribution of climatic regions using the Koppen system. A: moist tropical; B: dry climates; C: moist climates with mild winters; D: moist climates with severe winters; and E: polar climates.

Type A: Tropical Climates

Tropical climates are characterized by constant high temperatures with an average temperature of 64°F (18°C) or higher, and no winter season. Crops that are produced in these climates include sugarcane, cacao (cocoa beans), coffee, and bananas. There are several variations on this climate including the following:

Tropical Wet, Rain-Forest Climates

Tropical wet, rainforest climates have high temperatures (average of 80°F [2.7°C]) and rainfall (70–100 inches [178–254 centimeters]). The temperature and rainfall are relatively uniform throughout the year. Most of the region is concentrated within 10° of the equator, but sometimes extends beyond this range. The Amazon Basin of South America is an example of this climate. Rain forests in this region have a diversity of plant and animal species.

Tropical Wet and Dry Savannahs

Tropical wet and dry savannahs have a high annual precipitation, and a dry period in the winter months. This region is a transition between dry climates and tropical rain forests. The vegetation is native grassland with interspersed shrubs and trees. This climate occurs in Argentina, southern Florida, and Cuba.

Type B: Dry Climates

In **dry climates**, there is not enough precipitation for many types of plants to grow. Variations of this type of climate include the following:

Arid Desert Climates

Arid desert climates receive less than 5 inches (13 centimeters) of rain annually. They extend from northern Mexico into southwest United States. They include the Sonora and Mojave deserts. Vegetation is very drought tolerant and includes cacti, shrubs, and grasses that are used for grazing.

Semiarid Steppe Climates

Semiarid steppe climates occur in the western United States surrounding arid regions and extend eastward to western Minnesota. This region includes most of the short grass prairies and the Great Plains from the Dakotas to Texas. The epicenter of the Dust Bowl was the southern plain region of Texas, Oklahoma, and Kansas. Wheat is grown in this region, often under irrigation.

Type C: Moist, Mid-Latitude Climates with Mild Winters

Moist, **mid-latitude climates** have warm to hot summers with mild winters. The average temperature of the coldest month is below 64°F (18°C) and above 27°F (–3°C). This category includes humid subtropical climates, Mediterranean climates, and marine climates.

Humid Subtropical Climates

Humid subtropical climates occur in the southeast United States, where abundant precipitation occurs in the summer. Summer temperatures average about 80°F (27°C) and winter temperatures average 40–55°F (4–13°C). Rice, cotton, and tobacco are grown in this region.

Mediterranean Climates

Mediterranean climates (dry-summer subtropical) can be found in southern and central California. Average winter temperatures are typically 40–50°F (4–10°C), and summer temperatures are 70–80°F (21–27°C). A variety of vegetable crops, cotton, and alfalfa are produced year-round in this region. Citrus crops and grapes are also produced. Irrigation is necessary for profitable crop production in the summer.

Marine Climates

Marine climates with cool summers and moderate winters occur in coastal regions of northern California, Oregon, and Washington. The climate is moderated by air movement from the Pacific Ocean, and fog is common. The vegetation is mostly evergreens such as the redwoods of northern California. Horticultural crops such as apples, peas, and lettuce are important in this climate.

Type D: Moist Mid-Latitude with Cold Winters

These climates are associated with large landmasses and have warm summers and cold winters. The average temperature of the warmest month exceeds 50°F (10°C), and the coldest monthly average is below 27°F (–3°C). These climates can be found in humid continental, warm summer regions, as well as subpolar regions.

Humid Continental, Warm Summer Regions

Humid continental, warm summer regions can be found from Minnesota in the central United States to the east coast. Most rainfall occurs from May to September. A diversity of crops can be grown in this region. Corn, soybean, and small grains are grown as summer annuals. In the eastern United States, small grains and canola can be grown as winter annuals. Perennials such as alfalfa and red clover are grown.

Subpolar Regions

Subpolar regions include much of Canada and Alaska. They have severe winters. Precipitation is variable, and snow cover can last more than 120 days. Crops grown in this region include wheat, canola, and potato.

Type E: Polar Climates

This climate in the tundra and ice cap has extremely cold winters and cool summers. Tundra vegetation includes mosses, lichens, and shrubs. This climatic region is not of agricultural significance.

Precipitation and Temperature

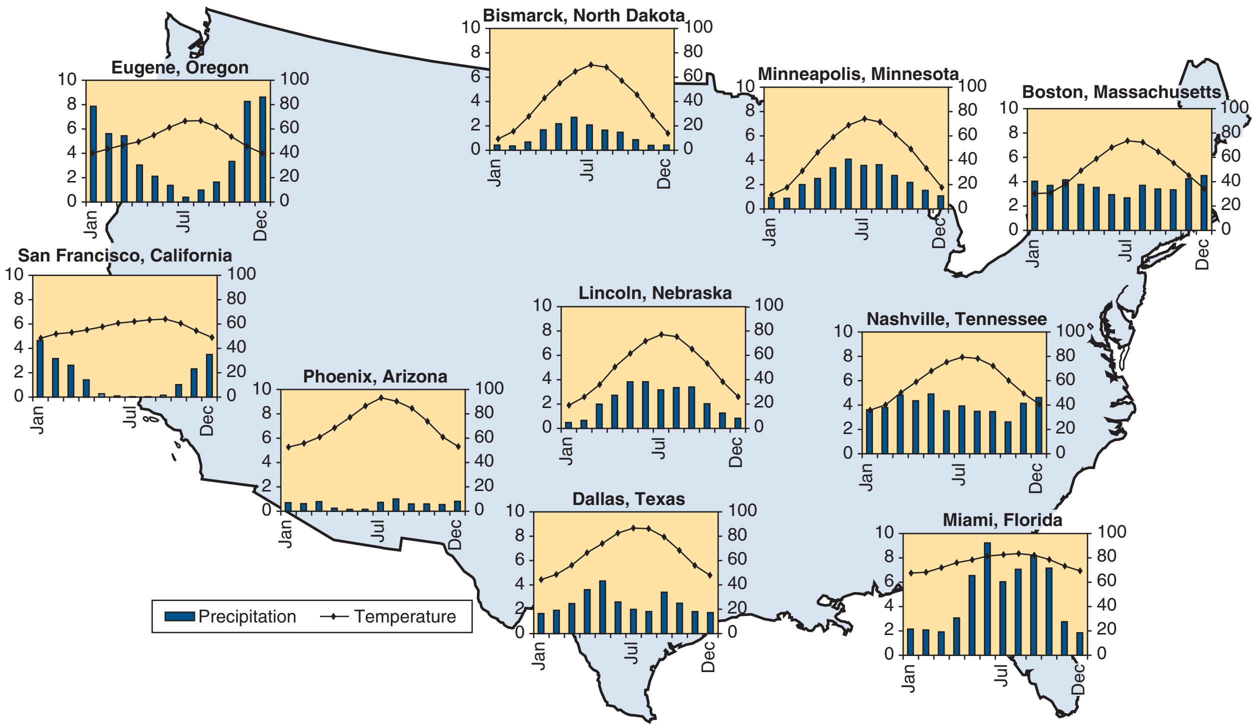
Two important features of climate that affect human activities and agricultural practices are precipitation and temperature. Temperature and precipitation variations associated with the climate are shown in the accompanying climographs for various U.S. cities (Figure 10-13). A climograph plots monthly average temperature and precipitation, providing a quick way of illustrating the climate of a place.

Precipitation

Precipitation falls mostly as rain and snow. In any form, precipitation provides water for plant growth. Water resource management is critical for efficient crop production. Water, an essential component of all plants, constitutes 75–90 percent of most plants. Water facilitates several important functions in plants. It provides turgor pressure for plant cells; it is a solvent and transports essential nutrients such as minerals and sugars; it is a component of chemical reactions; and it is a coolant.

The Water Cycle

The earth's water constantly circulates through the **water cycle** (Figure 10-14). About 97 percent of the earth's water is found as liquid in the oceans, about



Adapted from National Drought Mitigation Center (2007).

FIGURE 10-13 Climographs showing the temperature (°F) and precipitation (inches) patterns for regions of the United States.

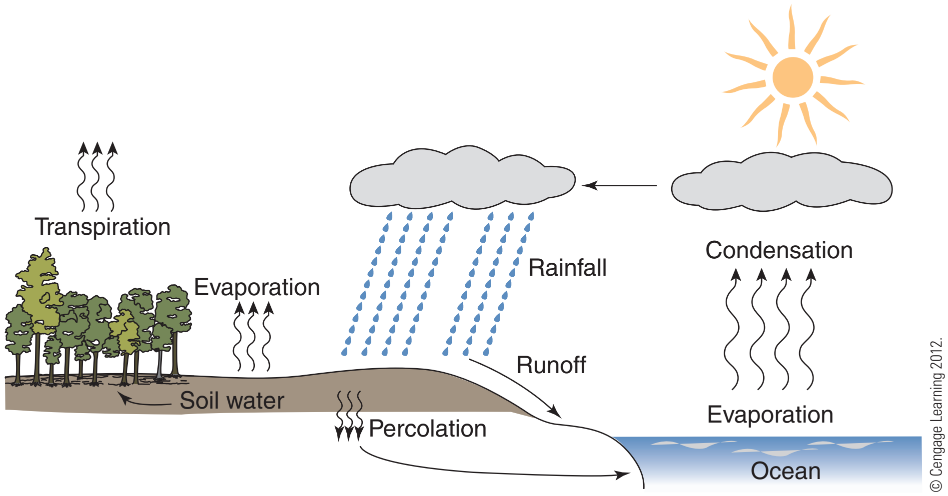


FIGURE 10-14
The earth's water cycle.

2 percent is found in solid form as glaciers and ice caps, and only 0.5 percent as groundwater on the earth's surface or as an atmospheric gas. Water vapor in the atmosphere is less than 0.01 percent of the total water on the earth. Because ocean water is saline, the freshwater available for human and animal consumption or for agricultural use is the most limiting factor in human population distribution and agricultural production systems.

Within the water cycle, oceans, lakes, ice caps, and glaciers are reservoirs for water storage. The sun's energy evaporates water from the surfaces of land, oceans, rivers, and lakes, and it drives plant transpiration. Evapotranspiration refers to the collective change of water from liquid to gas through evaporation and transpiration (see Chapter 8). Water vapor in the atmosphere can condense to form clouds. The movement of moisture-laden air is influenced by the spin and rotation of the earth and atmospheric temperature gradients. Precipitation that falls to the earth can run off into streams or rivers, evaporate, be held in the soil, or percolate through the soil into groundwater. Only water that is held in the soil is available for plant growth.

Water is an effective solvent for many chemicals. Fertilizer nutrients such as nitrate-nitrogen (NO_3-N) and some pesticides are moved by water from agricultural lands to water supplies and the ocean. This has created human health and environmental concerns. In addition, because of the surface tension and density of water, it can adhere to, suspend, and move soil minerals and organic matter, thus causing erosion.

Precipitation Patterns

Precipitation rates vary over the United States and partially reflect the climatic classification noted previously (also see Figure 10-15). There are four general precipitation regions.

- **Humid region**. These areas have more than 40 inches (102 centimeters) of rainfall per year and are located on the Pacific northwest coast, the Gulf region, and Atlantic coast states. These regions receive a significant amount of

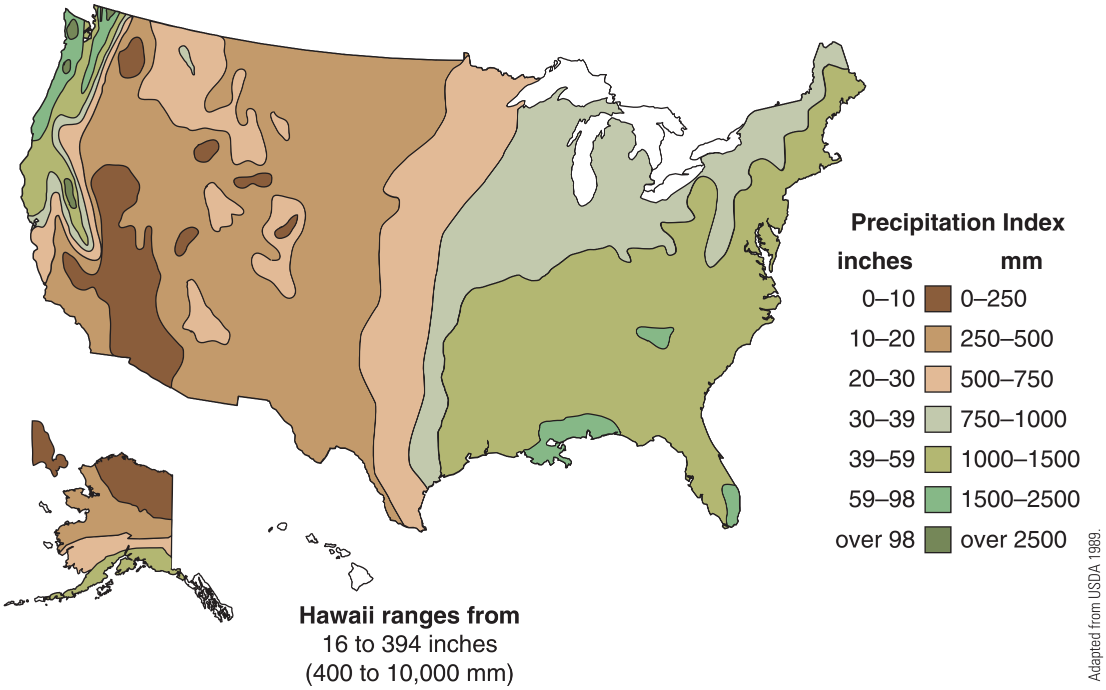


FIGURE 10-15 Average annual precipitation in the United States.

precipitation from the Pacific and Atlantic Oceans. In these areas, crops are normally grown without irrigation. The original vegetation was often forests.

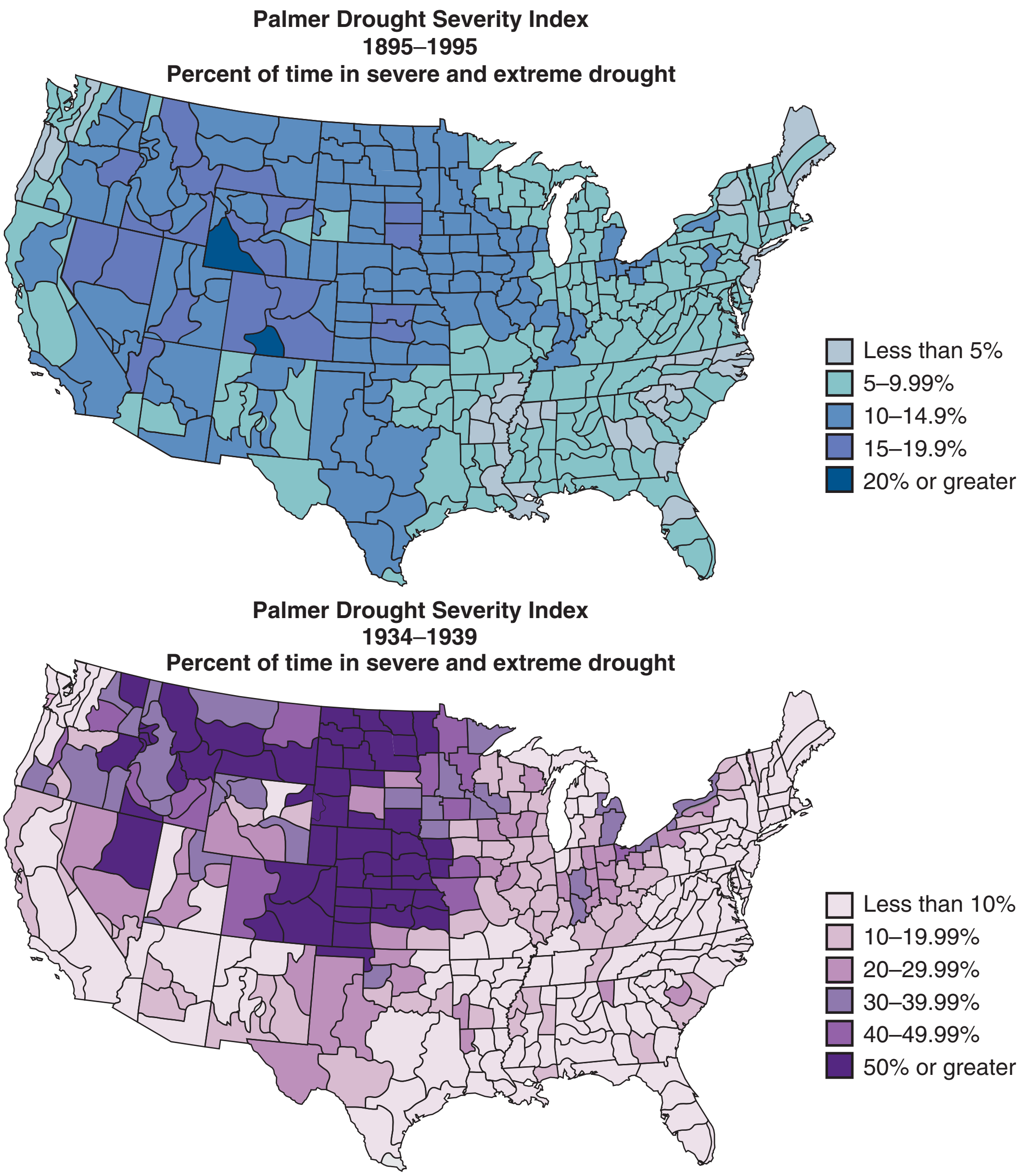
- **Semi-humid region**. These areas have 30 to 40 inches (76 to 102 centimeters) of precipitation. This region extends from Minnesota to the humid region in the east. Much of this region's original vegetation was forests. This region receives a significant amount of precipitation from moisture that moves northward from the Gulf of Mexico.
- **Semiarid region**. These areas have 10 to 20 inches (25 to 51 centimeters) of precipitation. This region includes Montana, North Dakota, and western Minnesota south to Texas. This region originally contained the short grass and tallgrass prairies. In much of this region, irrigation is required for summer grain crop production; otherwise winter grains are planted. Moisture conservation is often practiced.
- **Arid region**. These areas have 10 inches (25 centimeters) or less of precipitation. They include the arid Imperial Valley of southern California, as well as the dry areas in the southwest. These regions are directly affected by the presence of mountains in the Coast Range and Sierra Nevadas. Irrigation is required for crop production in these regions.

Extremes in Precipitation

Drought is a prolonged period of deficiency in normal precipitation, resulting in extensive damage to crops and their yields. It can also result in water shortages that affect the environment or human activities. Drought should not be confused

with semiarid or arid climates that have naturally low rainfall. Moisture-deficit effects on crops are enhanced by high temperatures that increase evapotranspiration rates.

The National Drought Mitigation Center (NDMC) at the University of Nebraska–Lincoln monitors drought and has calculated the spatial extent of drought in the United States. Some part of the United States has experienced a



Courtesy of NDMC (2007), McKee et al. (1993), and National Oceanic and Atmospheric Administration (1996).

FIGURE 10-16 The percentage of time in severe or extreme drought for two time periods: 1895–1995 and 1934–1939 (Dust Bowl). The Palmer Index uses temperature and rainfall information to determine long-term drought.

severe or extreme drought in each year from 1895 to 1995, and in 72 of those years, droughts covered more than 10 percent of the country (Figure 10-16). The annual average is 18.1 percent. One of the most historic droughts occurred during the 1930s. It was most severe in the Southern Plains of the United States and created the Dust Bowl. In July 1934, 65 percent of the United States experienced severe to extreme drought. The worst, recent drought event occurred in July 1988, with 36 percent of the country in severe or extreme drought.

The National Drought Mitigation Center summarized the relative economic losses in the United States due to drought and other catastrophes by using data from various sources including the Federal Emergency Management Agency (FEMA). Drought costs from $6 to $8 billion annually, floods cost $2.4 billion, and hurricanes from $1.2 to $4.8 billion.

In contrast to drought, **flooding** is excess water on the land. Excess precipitation or a high rate of snowmelt can result in water overflowing from rivers, streams, or ponds in low areas of some poorly drained soils. The moisture conditions due to flooding or high water tables can cause significant crop loss (Figure 10-17). When the soil-air space is filled with water many crop plants (other than rice) cannot survive the anaerobic conditions. Flooding and saturation of soils cause poor growth and death of plants. If plants do not die, they still suffer significant yield loss. Alfalfa suffers from nodule decay in addition to yield loss. Yield loss is related to several factors:

- The primary reason that flooding and very wet soil damage plants is their impact on respiration, the oxygen-dependent process by which plant cells convert energy for maintenance, and active uptake of nutrients. Flooding fills soil pores with water and prevents oxygen diffusion to plant roots. In the absence of respiration, carbon dioxide and other compounds like ethanol and butyric acid accumulate near roots. Consequently, plant roots become nonfunctional and ultimately die.



Tim McCabe, USDA-NCRS.

FIGURE 10-17
Flooding can destroy plants directly through the force of water or debris, and it also kills by creating saturated and anaerobic soils.

- Without functioning roots, plants cannot take up water (even though the root may be submerged) or nutrients for transport to the shoot. Legumes like soybean and alfalfa suffer nodule delay and lose the capacity for biological nitrogen fixation.
- Wet soils have a greater incidence of soil-borne, root and crown diseases including *Phytophthora* spp. and *Pythium* spp.
- Saturated and flooded soils can lead to loss of nitrogen fertilizers from the plant root zone. This is detrimental to annual crops like corn and small grains that depend on nitrogen fertilization for high yields.

The extent to which flooding injures crops is dependent on several factors including duration of flooding, air and water temperatures, and stage of plant growth. Dormant perennials like alfalfa and forage grasses that have low levels of metabolism can tolerate extended flooding for about 2 weeks when soil temperatures are low in early spring and fall. Corn and soybean can tolerate flooding for only 2–4 days, but higher temperatures increase the risk of injury. For example, if water and soil temperatures are above 80°F (27°C), plant survival is greatly diminished.

Temperature

All energy on the earth is derived from the sun. **Temperature** is a measure of the intensity of heat or energy content of the air, inert matter, or of an organism. Temperature in the United States is commonly measured on a Fahrenheit scale that uses 32°F as a freezing point for water and 212°F as a boiling point for water. Other countries use the centigrade (Celsius) scale. It uses a water-freezing point of 0°C and a boiling point of 100°C.

Temperature influences the type of crop grown and its productivity. Latitude, season, proximity to water, and altitude influence temperature and result in a range of temperatures in the United States that affect plant growth and production.

Season and Latitude Effects

Temperatures are typically warmest in the summer and coldest in the winter, but they are greatly influenced by the area's latitude, altitude, and proximity to water. Because of seasonal changes in the amount of solar radiation received at northern latitudes, extreme variation in winter and summer temperatures occurs. At latitudes closer to the equator, winter and summer air-temperature fluctuations are minimal.

Latitude also has a distinct effect on the length of growing season (frost-free days). The growing season is defined as the time between the last killing frost (0°C) in the spring and the first killing frost in the fall. The growing season in the United States varies from more than 300 days in the most southern latitudes to only 70 days in some northern latitudes. As described previously in the discussion about climatic factors, elevation and proximity to large bodies of water also influence temperature.

Diurnal Effects

Temperatures display a diurnal (daily) cycle of heating and cooling due to variation in the sun's energy. At noon, when the sun is at its zenith, maximum heating occurs. However, maximum daily air temperatures are usually two to four hours later because of the heat radiation from the earth's surface.

TABLE 10-3

Minimum, optimum, and maximum temperatures for growth of temperate and tropical plant species. Optimum: temperature at which a plant reaction or function occurs most efficiently. Minimum: the lowest temperature at which a reaction or function will occur. Maximum: the highest temperature at which a reaction or function will occur. *Adapted from Decoteau (2005).*

		Minimum		Optimum		Maximum	
Plant type	Example	°F	°C	°F	°C	°F	°C
Temperate, cool season	Wheat, alfalfa, smooth bromegrass	41	5	59–86	15–30	95–104	35–40
Tropical, warm season	Corn, sorghum, soybean, cotton	50	10	86–95	30–35	113	45

Temperature Effects on Plant Processes

Temperature has a significant effect on physical and biochemical processes. Temperature affects the density of all nonliving substances and especially the state of water, which constitutes from 80 percent to 90 percent of plants. At temperatures below 32°F (0°C), water becomes a solid and cannot flow, whereas above 212°F (100°C), water changes from a liquid to a gas. At temperatures between freezing and boiling, water flow rate (viscosity) within the plant is affected, as is reactivity in biochemical reactions.

Plant species vary in their response to temperatures, but all have optimum temperatures for growth (Table 10-3). Low and high extremes in temperature can reduce a plant's growth and cause its death. Low temperatures affect cell structure, whereas high temperatures denature (break down) enzyme systems in the cell.

- **Freezing injury** occurs when ice forms in cells and damages the cell membrane and cell organelles, or when extracellular ice causes cell dehydration.
- **Chilling injury** at above freezing temperatures can occur to crops such as corn, banana, and tomato from tropical regions. The damage is due to disruption of plant cell membrane integrity.
- **Heat injury** occurs at overly high temperatures. Heat injury occurs at 120°F (49°C) or above, with some species sensitive to temperatures as low as 95°F (35°C). High temperatures can interfere with metabolic processes or cause plant cells to collapse.

Approaches to Managing Environmental Resources

Farmers employ diverse strategies to efficiently use environmental resources and to minimize risk due to climatic conditions. They select crop species and crop varieties based on the crops' adaptation to specific climates. Farmers also use management strategies appropriate for the crops they grow.

Crops

Crops to be grown can be chosen using diverse criteria including adaptation to various temperature and moisture regimes.

Adaptation to Temperature

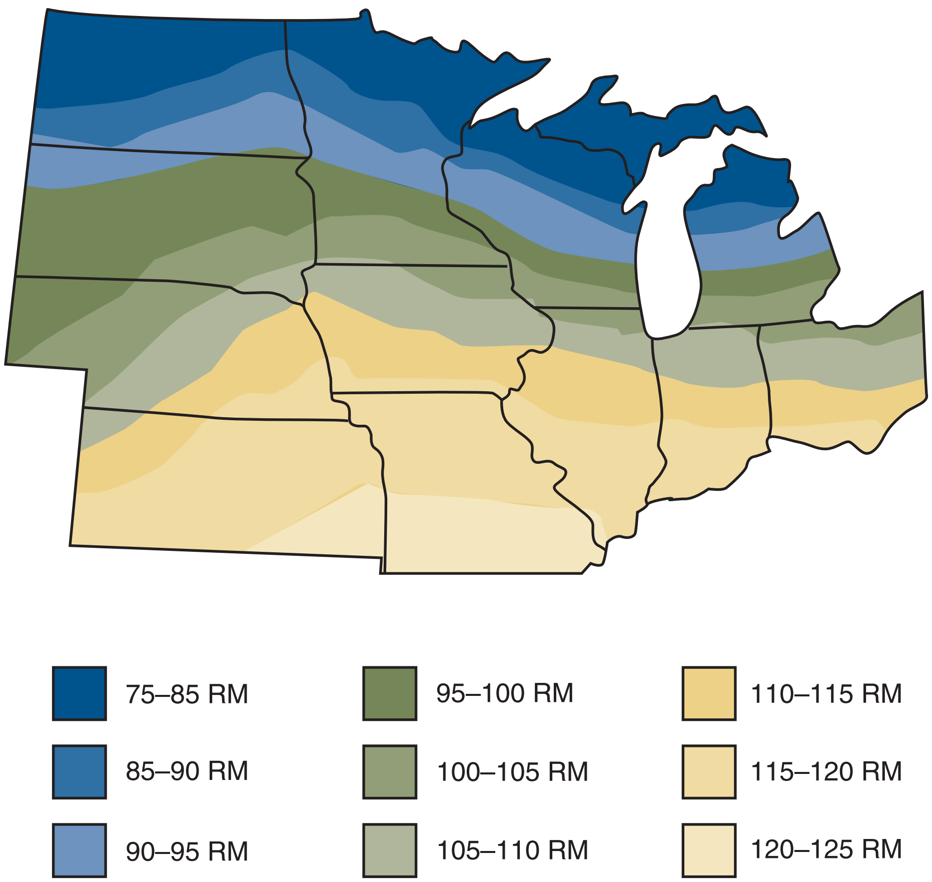
Crops are classified as **temperate**, **tropical**, or **subtropical** based on their region of origin or optimum temperature regime for growth (Table 10-3).

- Tropical plants originate at or near the equator and between the Tropics of Capricorn and Cancer (23° north and south of the equator). Examples include corn, soybean, cotton, and sugarcane. Tropical plants are often called *warm-season* plants and grow best in warm climates, at temperatures above 50°F (10°C). Temperatures below 32°F (0°C) kill tropical plants. Tropical plants such as corn and soybean are now grown extensively in northern latitudes as summer annual crops. They are planted in the spring after the last killing frost and are harvested in the fall.
- Temperate plants are from regions of distinct seasonal change in temperature. Examples of temperate plants include alfalfa, smooth bromegrass, wheat, and barley. They are also called *cool-season* plants. They are grown from the Arctic, where the growing season is short and the winter is long and cold, to the southern United States, where the growing season is very long and the winter is mild. In northern latitudes, cool-season plants grow best in spring and fall. In regions with hot summers, cool-season plants often become semidormant. Sometimes temperate species can be used as winter crops in tropical and subtropical areas. For example, temperate species such as annual ryegrass, winter wheat, and crimson clover are grown in some regions of the south as winter annuals. They are planted in the fall, are used during the winter, and die in the spring before the onset of high summer temperatures.
- Subtropical crops border the tropical and temperate regions. Though grown best at warmer temperatures, they tolerate some freezing temperatures.

Crop Variation

Within the broad categories such as temperate crops and tropical crops, individual crop species and varieties within crop species vary in their tolerance of temperature.

- **Spring and winter wheat.** Winter wheat varieties that are seeded in the fall have a greater cold tolerance than spring wheat varieties that are seeded in early spring.
- **Alfalfa.** Alfalfa varieties vary in their winter hardiness. Some are adapted to the cold regions of the northern United States and Canada, whereas others are not winter hardy and are more productive in the Southwest and West.
- **Corn hybrids.** Breeders have selected hybrids that vary in their relative maturity to fit the frost-free growing period within a region (Figure 10-18). Relative maturity (RM) is a system that denotes the average days to physiological



Adapted from University of Minnesota Extension Service and others.

FIGURE 10-18 Corn hybrid relative maturity recommendations for the Midwest. Relative maturity (RM) is a system to enable identification of corn-hybrid adaptation to the growing-season length in a region.

maturity for a particular hybrid. Selection of the appropriate variety/hybrid will maximize use of environmental resources for grain production before the first killing frost occurs. These hybrids do not differ substantially in cold tolerance but are adapted to northern regions because of their early maturity.

Adaptation to Moisture Stress

Plants are classified into three general categories according to their water requirements or tolerance to wet conditions.

- **Hydrophytes** are plants that grow in water. They have the ability to extract oxygen from the water. Examples include wild rice and cultivated rice.
- **Mesophytes** are "normal" plants that are adapted to tropical and temperature regions and depend on precipitation for growth and development. Examples include corn, soybean, and alfalfa.
- **Xerophytes** are plants that have specialized morphological features such as hairy leaves, thick cuticles, or a small leaf area, enabling them to grow in very dry environments. Examples are cacti that also have a capacity to store water.

TABLE 10-4

Water-use efficiency of several crops. Water use efficiency is described as the amount of plant dry matter produced for an equal amount of water used. *Adapted from Barden et al. (1987)*.

Crop	Water use efficiency, relative rating
Alfalfa	1 (least efficient)
Barley	2
Soybean	3
Oats	4
Wheat	5
Corn	7
Sorghum	8 (most efficient)

Crops vary in their water use efficiency (Table 10-4), and, if moisture supplies are limited, crops can be selected to provide an economic return. A crop's water use efficiency is measured as the amount of water required to produce an equal quantity of dry matter. For example, in the semiarid southwestern region of the United States, sorghum is widely grown. Alfalfa is grown only in northern latitudes where moisture is abundant or in semiarid regions where irrigation is possible.

Cultural Practices

In addition to selecting crops for environmental adaptation within a region, some management strategies optimize utilization of environmental resources.

Management of Crop Residues

Producers can influence soil temperature and soil moisture by varying the amount of crop residue left on the soil surface. Examples of crop residues include corn stover and wheat straw left after grain harvest. The traditional approach of moldboard tillage incorporates crop residues (see Chapter 14). Conservation tillage leaves residues on the soil surface and reduces soil erosion. Crop residue on the soil surface increases absorption of water from precipitation and also conserves soil moisture by decreasing water evaporation from the soil surface. Surface residues affect soil temperatures by buffering against changes in air temperature. They slow soil temperature warm-up in fields in the spring. They can also insulate the soil and plants from freezing in the winter. Crop residue left on the soil surface can also be called **mulch**. However, the term *mulch* is most often used to describe the use of straw, wood chips, or plastic by homeowners for weed control and moisture conservation in ornamental and horticultural crop production.

Fallowing

Fallowing is a strategy for accumulating moisture in the soil. It is used in semiarid regions in the northern and southern Great Plains, where normal precipitation is limited during the summer growing season. The land in rotation is not cropped

Crop Insurance

Farming practices are adapted to typical or normal weather patterns within a region. However, because of its dependence on the weather, farming is a very risky business. Hail, flooding, frost, and drought are weather conditions that can damage or destroy crops. Nonenvironmental factors that can harm crops include insects and disease. Farmers may choose to purchase **crop insurance** to reduce the risk of financial losses of yield and crop failure due to natural causes. Crop insurance can also protect against unfavorable drops in market prices. Crop insurance can be divided into two types: policies that cover yield loss or ones that cover revenue loss.

The federal government and private insurers provide different forms of crop insurance. The federal crop insurance program is managed by the USDA Risk Management Agency (RMA). The majority of crop insurance programs, whether federal or private, provide payments when yields or potential revenues decline by 30 percent or more; but coverage level depends upon a farmer's willingness to pay increasing premiums. Corn, soybeans, rice, wheat, cotton, grain sorghum, barley, and canola constitute the majority of crops covered under crop insurance.

In addition to crop insurance, the federal government provides protection from some natural disasters to all farmers. When a disaster is declared after a devastating natural event such as widespread flooding and drought, disaster payments are made to affected farmers who can prove a loss. The Environmental Working Group (http://farm.ewg.org/) estimates that payments of about $18 billion dollars were made for crops and livestock from 1995–2009.

and is kept free of volunteer weeds by using either shallow cultivation or herbicides (chemical fallow). Water is not lost through plant water use (transpiration) because crops are not grown during the summer, and volunteer weeds are controlled. Although some water evaporates from the soil surface following rainfall, about 25 percent of the rainfall can be stored for the following crop. Fallowing systems that leave undisturbed crop residue on the soil surface also increase water intake and reduce water runoff. In Washington, North Dakota, and Nebraska, wheat may be grown in a rotation following one year of chemical fallow. Fallowing also increases the availability of nitrogen in some soils.

Irrigation

In semiarid regions and on low moisture-holding soils throughout the United States, irrigation is often practiced to meet the water needs of crops. **Irrigation** is the supplementation of precipitation with water from another source in order to grow crops. Crop irrigation is currently the largest use of freshwater in the

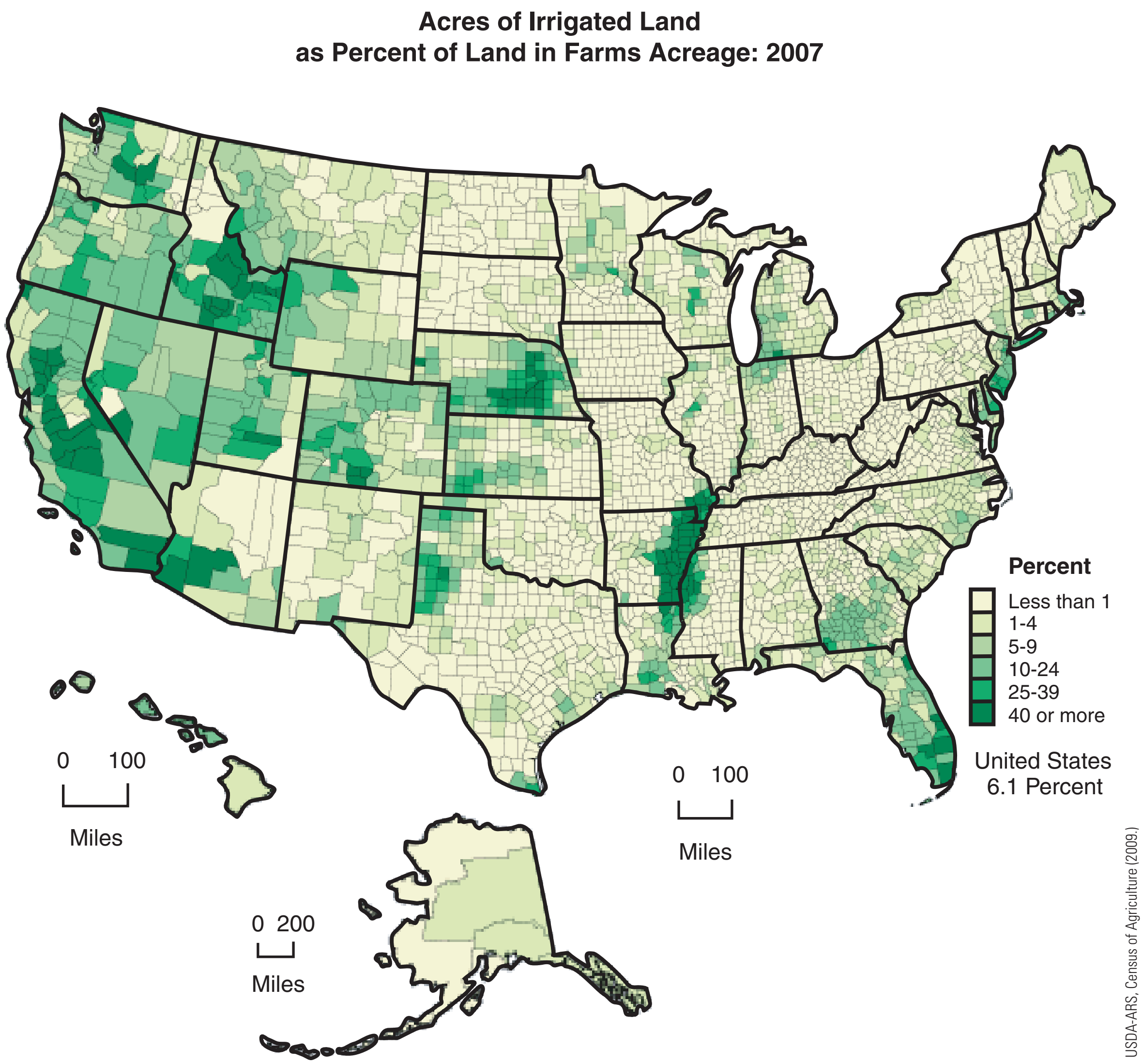


FIGURE 10-19 Irrigated land on farms in 2007.

United States. In 2003, about 53 million acres (21 million hectares) of cropland were irrigated. Most of the irrigation occurs in the western regions of the United States, where precipitation levels are inadequate or variable (Figure 10-19). The type of irrigation system depends on the crop, region, and topography. Irrigation can be divided into two categories: surface irrigation and sprinkler irrigation.

Surface irrigation, or gravity flow irrigation, applies water directly to the soil surface via flood or furrow irrigation (Figure 10-20). Water is moved to fields in ditches or large pipes and reaches the field as a uniform flood, or in furrows or small ditches between the crop rows. Gravity flow irrigation is used in areas where the land is level or is graded to achieve uniform flooding and drainage.



FIGURE 10-20
Level basin flood irrigation of wheat in Arizona.

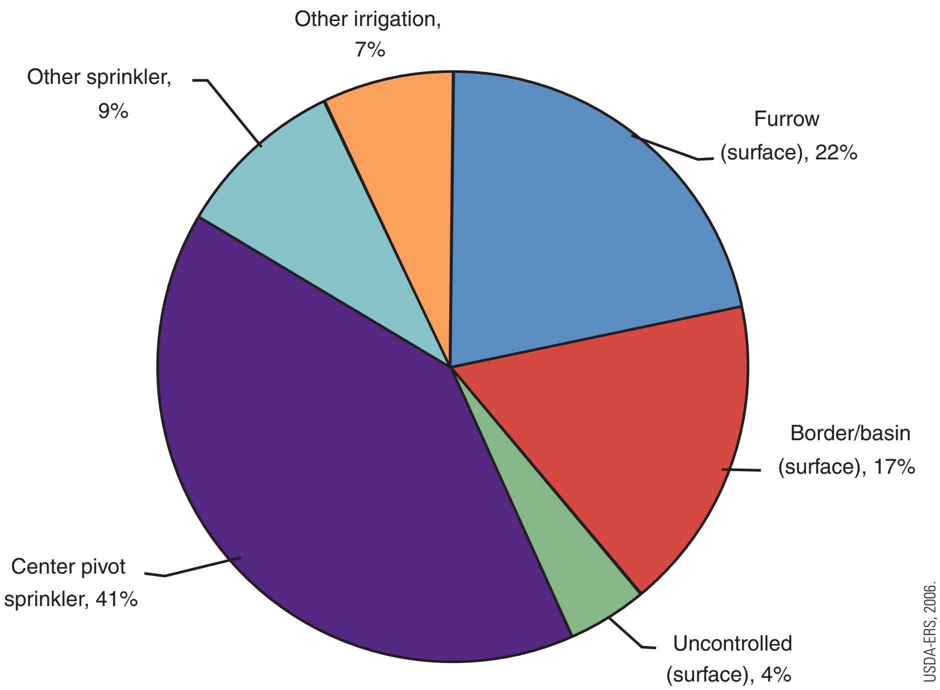


FIGURE 10-21
Irrigation systems by type in the United States, 2003.

This type of irrigation is being used less in the United States, but still accounts for 44 percent of all irrigated land, or about 53 million acres (21 million hectares) (Figure 10-21).

Traditional surface irrigation, which includes furrow, border, basin, and flood irrigation, is generally less efficient because it supplies more water than needed. Up to 50 percent of the water applied may not be used directly by the crop because it leaves as runoff or drains past the crop-root zone. Basin or paddy irrigation is used to supply water to rice that is grown in an area enclosed by dykes.

Pumps are used to control flooding and to remove the water, allowing for harvest.

Modern surface systems are much more efficient and lose only 10–20 percent of water. Advancements in surface irrigation involve land leveling with lasers for consistent water application over the field, reducing water loss during transport to the field, and capturing water runoff for reuse.

Sprinkler irrigation applies pressurized water through the air by using pipe and elevated sprinklers. Sprinkler irrigation accounts for about half (27 million acres or 11 million hectares) of all irrigation. These systems are more efficient than surface irrigation. Center pivot systems, the most common sprinkler system used in the United States, are an example of a sprinkler system in which the overhead pipe and sprinklers rotate 360° around a central point (Figures 10-22 and 10-23). Less common are linear (sometimes called *lateral*) move systems. Linear move sprinkler irrigation is similar to center pivot, except that the sprinkler moves in one direction rather than in a circle.

Other irrigation systems besides surface and sprinkler include subsurface irrigation, where the water table is brought up to the crops' roots from below; and drip irrigation, where water is delivered directly to the crop at its roots by irrigation tubing. Drip irrigation is used most often on high-value horticultural crops. Neither of these systems is commonly used for agronomic crops.

Irrigation Strategies

There are several strategies to determine how and when to apply irrigation to a crop. Ideally, crop water needs should be met without overapplying water. Over application wastes water and increases production costs.



Doug Wilson, USDA-ARS.

FIGURE 10-22
Center pivot irrigation. More than 100 center pivot sprinklers controlled by a central computer irrigate wheat, alfalfa, potatoes, and melons along the Columbia River near Hermiston, Oregon.



Gene Alexander, NRCS.

FIGURE 10-23
Sprinkler irrigation of wheat in Colorado with a center pivot irrigation system.

TABLE 10-5

Average crop water use (evapotranspiration) for corn as a function of growth stage and air temperature. *Adapted from Minnesota Extension Service (2002.)*

Average water use for corn in inches/day								
		Week after emergence						
Temperature		2	5	8	9	11	14	15
°F	°C							
50–59	10–15	0.02	0.05	0.09	0.09	0.1	0.07	0.06
60–70	16–21	0.03	0.08	0.12	0.13	0.14	0.11	0.09
71–79	21–26	0.04	0.1	0.16	0.17	0.19	0.14	0.11
81–90	27–32	0.05	0.13	0.2	0.22	0.23	0.17	0.14
91–99	32–37	0.06	0.15	0.24	0.26	0.27	0.2	0.17
		↑	↑	↑	↑	↑	↑	↑
Growth stage		3-leaf	8-leaf	1st tassel	Silk	Blister kernel	Early dent	Dent

Irrigation can be applied based on measurement of soil moisture. With this strategy, the soil moisture is continuously monitored, and water is applied when the level reaches a predetermined threshold (such as 25 percent of the water-holding capacity of the soil) for each crop on a specific soil. See Chapter 12 for more information on soil moisture.

Another strategy is to apply water based on estimation of crop water use. The "checkbook" system bases irrigation on total crop water use or evapotranspiration at a specific grown stage (Table 10-5). The crop water needs that are not supplied by precipitation are provided by irrigation. Crop water use depends on many factors including crop type, stage of growth, climatic conditions, and soil moisture. Daily crop water use can be estimated from these generalized tables by observing the maximum daily temperature, crop growth stage, and the weeks after

emergence. Irrigation efficiency can be increased if soil-moisture status is monitored periodically.

Drainage of Cropland

Drainage systems are used on many agricultural soils that have excess soil water that interferes with agricultural operations and with normal plant growth. Excess water can delay planting in the spring and interfere with harvesting in the fall. Removal of water in the spring can also raise soil temperatures and increase the rate of crop growth. Drainage systems can rapidly remove excess water due to heavy rainfall and also lower the water table to allow for adequate oxygen movement into the soil. All effective drainage systems take advantage of the principle that with gravity, water flows downstream until it ultimately reaches the ocean. Drainage can involve surface or subsurface systems.

- Surface drainage systems involve excavating channels or ditches that eventually lead into streams and rivers. Water flows laterally over or through the soil until it reaches the channel.
- Subsurface drainage is accomplished by burying perforated plastic pipe to a depth of 2–6 feet (0.61–1.83 meters; Figures 10-24 and 10-25). As the soil becomes saturated, water flows into the pipe. The pipes are installed so as to slope toward either larger conduits or open ditches that flow into streams. Subsurface drainage tile can be installed in different patterns and spacing depending on the drainage characteristics of the land and slope.

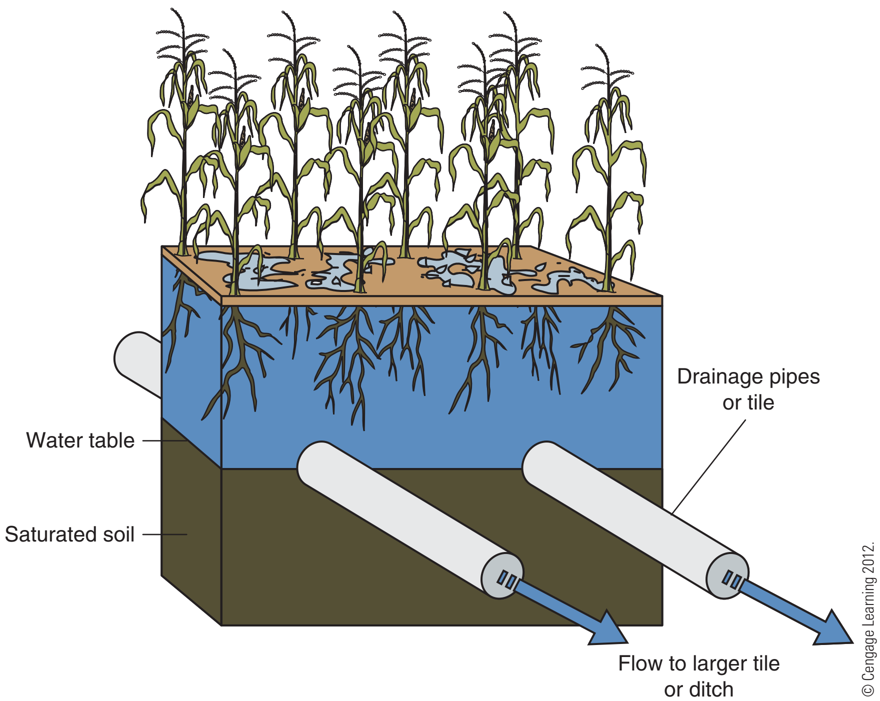


FIGURE 10-24 Perforated tile drainage removes water to facilitate field operations and crop growth.

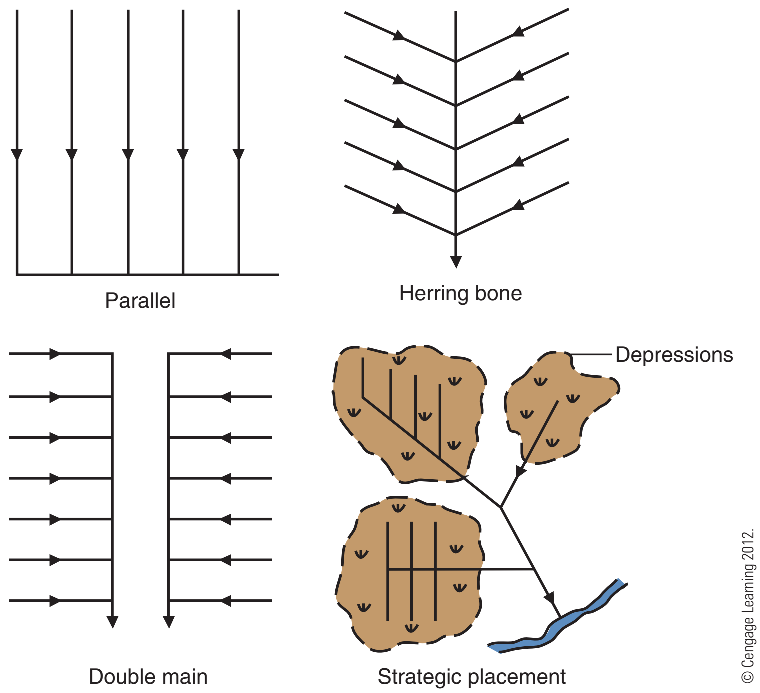


FIGURE 10-25
Patterns of tile drainage for agriculture. Tiles ultimately drain into streams or drainage ditches that lead to rivers and oceans.

TABLE 10-6

Some of the advantages and disadvantages of drainage systems. *Adapted from Brady and Weil (2000).*

Advantages	Disadvantages
Improved soil workability allowing earlier and more timely field operations	Increased nutrient and pesticide leaching
Increased productivity of crops due to increased oxygen	Loss of wildlife habitat
Reduced incidence of fungal crop disease	Installation of tile costly and highly regulated
Decreased methane production	Increased soil organic matter loss
Removal of excess soil salts	Increased flooding in rivers to which drainage flows

Artificial drainage has benefitted farming greatly by increasing the amount of land that can be successfully farmed, but it also has some drawbacks (Table 10-6). Some of the negative effects such as nutrient and pesticide leaching can be mitigated by proper management of fertilizer and pesticide application. The use of perennial crops in rotations can also reduce leaching and decrease the amount of water that flows into tiling systems.

Crop Management

In most regions, recommended dates for planting crops have been established. These **planting dates** were established to maximize capture of solar energy and use of water during a growing season while minimizing risk of injury due to untimely frosts. For example, in most of Iowa and southern Minnesota, spring small grains such as oat and wheat are planted in early April because they germinate and grow well under cool spring conditions. They mature in July and August. In contrast, corn and soybean are planted from late April to early May, when soil temperatures are warmer. These crops mature in the fall. Additional discussion on planting dates is provided in Chapter 14.

Plant populations or planting rates are adjusted to provide for optimum light interception and use of soil moisture throughout the growing season. Recommendations provided by universities and private consultants are focused on optimizing yield while minimizing seed costs. Additional discussion on plant populations is provided in Chapter 14.

Weeds compete with crops for essential growth resources including light, water, and nutrients. Consequently, control of weeds is essential for profitable crop production. Chapter 15 describes approaches to weed control.

The Colorado River: A Dwindling Resource for Growing Needs

The 1500-mile-long Colorado River begins in the Rocky Mountain National Park in Colorado and flows through Utah, Arizona, Nevada, California, and Mexico (Figure 10-26). Its watershed is about 250,000 square miles. On its way to the Gulf of California, it passes through the Grand Canyon. Its flow has been altered by the Glenn Canyon and Hoover dams and diverted for agricultural and urban uses.

The American Southwest has an arid environment with low rainfall and extreme summer temperatures. Thus, water is a valuable resource and there is not enough to meet all the competing needs. Agriculture and urban development of the southwestern United States are dependent on the Colorado River (Figure 10-27). About 4.5 million acres (1.6 million hectares) are irrigated for agricultural production.

The Colorado River Compact of 1922, along with a complex set of newer laws, continues to govern water usage. The entities that share the water each get a percentage of the available water (Table 10-7). The states in the upper basin do not use as much water as states in the lower basin, and those excess allocations have been used by California.

The numerous dams, reservoirs, and canals along the length of the river have caused significant changes to the original ecosystem. So much water is diverted from the river that it usually does not reach its endpoint in the Gulf of California. Several species of fish have become endangered as their habitat disappeared.

Drought in the Southwest has reduced the amount of water available from the Colorado River, and reservoirs are becoming depleted. Historical records indicate that this lower amount of water is closer to the norm than



FIGURE 10-26 The Colorado River in Nevada.

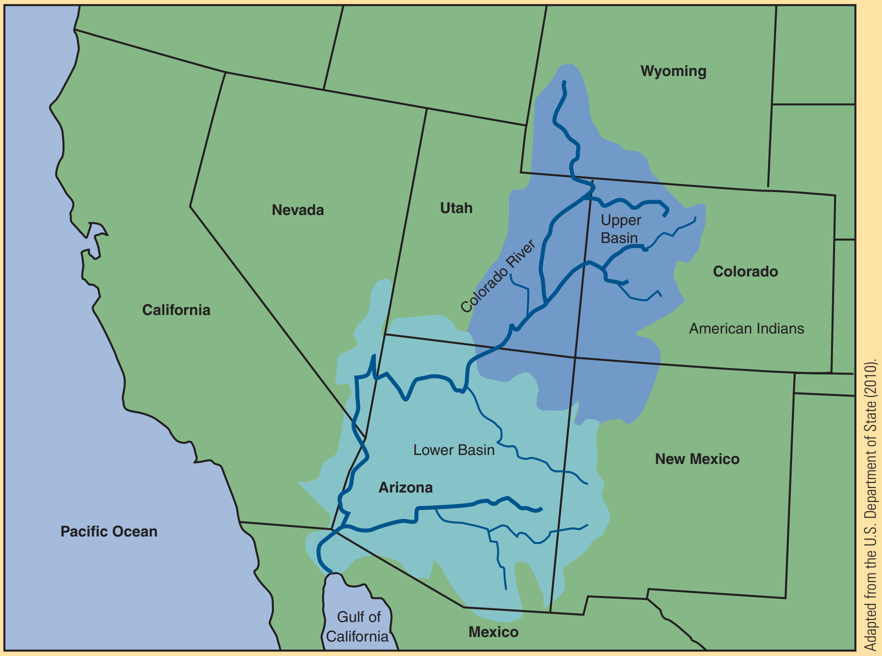


FIGURE 10-27 The Colorado River drainage basin.

(*Continued*)

TABLE 10-7

Amount and primary use of water taken from the Colorado River. *Adapted from the U.S. Department of State (2010).*

	Amount of water used		
Entity	Billion gallons	Million cubic meters	Primary use
California	1434	5427	Agriculture
Arizona	912	3454	Agriculture
Colorado	847	3207	Agriculture/urban areas
Mexico	489	1850	Agriculture
Utah	456	1725	Agriculture
American Indians	326	1233	Agriculture
New Mexico	211	800	Agriculture
Wyoming	195	740	Agriculture
Nevada	98	370	Urban areas (Las Vegas)

was previously thought. Because of the lessened flow, interim water-usage rules tie how much water is removed from the river based on the level of Lake Mead. The lower the level, the less water California, Arizona, and Nevada will receive. Water conservation has become a necessity in the Southwest to protect water resources. With populations growing in all the states, there has been discussion on changing the allocations, always a contentious subject. In the future, agriculture of the region may be diminished.

In the late 1980s, the late Marc Reisner, an environmentalist, published *Cadillac Desert* about water policy in the western United States. The book and a resulting Public Broadcasting Service (PBS) series describe the importance of water management in development of the West and the roles of U.S. government and state agencies in water policy. It also describes how twentieth-century-based water-use policies have had long-term ecological, economic, and sociological impacts.

Review Questions

1. What is the source of all of the energy on the earth, and how does this drive our climates?
2. What are the main influences on the energy the earth receives?
3. Describe the three components of light that influence plant growth.

4. Discuss the different layers of the atmosphere. What are the different layers, and how do they influence human and plant life?
5. How does the atmosphere protect the earth from harmful radiation?
6. Describe how the atmosphere helps maintain surface temperature.
7. What is our atmosphere predominantly made up of?
8. What is global warming, and what might it be caused by?
9. What is the difference between climate and weather?
10. What are the five different climate regions classified by the Koppen system?
11. Agriculture is affected by what two components of climate?
12. Describe the water cycle.
13. Identify the different precipitation regions in the United States.
14. How does temperature affect plants?
15. What are some practices that producers can engage in to manage soil temperature and moisture?
16. Describe fallowing and its purpose.
17. How do planting dates and rates help producers manage their crops?
18. Identify and describe an irrigation strategy.

Critical Thinking

1. Crop irrigation has become an accepted practice in the United States. However, in some regions, groundwater is becoming depleted, and there is now competition for the water between humans and agriculture. Consider the pros and cons of using water for crop irrigation. Should there be federal policy to regulate irrigation?
2. Global warming and its effect on life on the earth have been widely discussed. Are there solutions to global warming? Do you think that global warming will affect your life?
3. Seasonal changes influence many aspects of our lives. Identify some effects on the changing seasons on your personal life, on nature, and on agriculture in your region.
4. What type of climate occurs where you live? How does it affect the plants and crops that are grown where you live?

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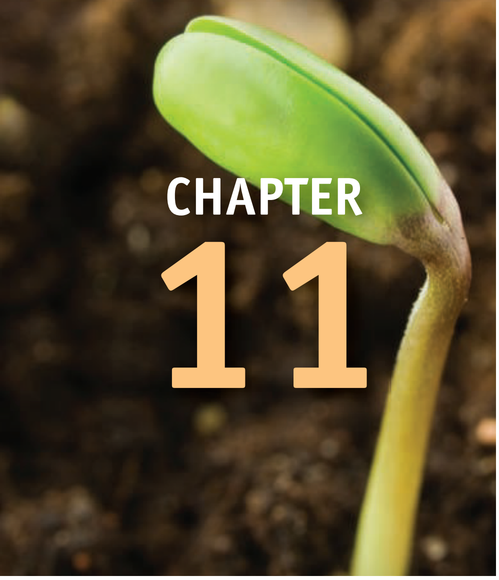
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CHAPTER 11

Agroecosystems





Key Concepts

- Ecology is the science dealing with relationships among biological organisms and their interactions with the environment.
- Ecosystems provide some unique services and have some unique characteristics such as species diversity, ecological succession, food chains, and nutrient cycles.
- Biomes are biotic communities containing specific communities of plants and animals. Biomes develop under the prevailing rainfall, temperature, and sunlight patterns.
- Humans manage agroecosystems to produce food and fiber. They differ from ecosystems in that they lack species diversity, rely on plant and animal breeding, and often have high levels of nutrient and energy inputs and losses.
- Oversimplification of agroecosystems has led to social and ecological disasters such as the Irish potato famine and the Dust Bowl.
- Sustainable agriculture maintains the soil and environmental resources for future generations and provides for profitable production of food, fiber, or energy to meet societal needs.

Key Terms

abiotic
agroecosystem
anhydrous ammonia
atmospheric fixation
biological magnification
biome
biosphere
biotic
carbon cycle
carbon fixation
consumer
conventional agriculture
dead zone
denitrification
desert
Dust Bowl
ecological pyramid
ecological succession
ecology
ecosystem
erosion
food chain
forest
fossil fuel
grassland
Green Revolution
habitat
humus
hypoxia
immobilization
industrial fixation
industrialization of agriculture

mineralization
niche
nitrate
nitrification
nitrogen cycle
plant succession
primary consumer
primary producer
secondary consumer
sustainable agriculture
tundra
volatilization

Introduction

Ecology is the science dealing with the mutual relationships among biological organisms (plant, animal, insect, and microbe) and their interactions with the environment. The word *ecology* is derived from the Greek word *oikos*, which means house. Our house is the environment in which we live, and we have responsibility for its stewardship. It is important to learn about the earth's environment and how humans have modified it in producing food, fiber, and shelter. We will discuss the importance of agriculture in sustaining our environment for the future.

Ecosystems

Organisms and their environments collectively function in an **ecosystem**. In ecosystems, organisms are the biological component (**biotic**), whereas environmental (nonliving) components are called **abiotic** (Figure 11-1). Ecosystems vary in size. As we study the environment, we recognize that the largest ecosystem is the entire earth's **biosphere**. The earth's biosphere ranges from the depths of the ocean to the top of the tallest mountain, a distance of more than 10 miles (16 kilometers).

Within the larger biosphere of the earth, we find ecosystems of various sizes containing populations with specific organisms and communities of all biological organisms living together. An example of a smaller scale ecosystem is a tallgrass prairie, such as that found in the Great Plains of what is now the United States, before European settlement. The biotic factors included plants such as big bluestem, little bluestem, Indiangrass, and prairie clover; animals such as bison, antelope, and jackrabbits; insects such as flies and mosquitoes; and microorganisms such as fungi and bacteria (Figure 11-1). The abiotic factors include water, minerals, sun, and the air.

We recognize that very few natural ecosystems have not been affected by human activity. Most are not in equilibrium and often have high levels of nutrient and energy inputs and losses. In the practice of agriculture, humans have developed **agroecosystems** that are ecosystems modified to produce fiber, food, and shelter. These agroecosystems are the foundation for human societies, but they have resulted in major changes in the earth's environment. Examination of a natural ecosystem's characteristics allows us to consider approaches to make our agricultural practices more sustainable and also to focus on the preservation of the components of some natural ecosystems. Ecosystems have potential to provide a number of important services to our society (Table 11-1).

Characteristics of Ecosystems

Ecosystems have many processes and characteristics including food chains, nutrient cycles, plant succession, competitive exclusion, and diversity.

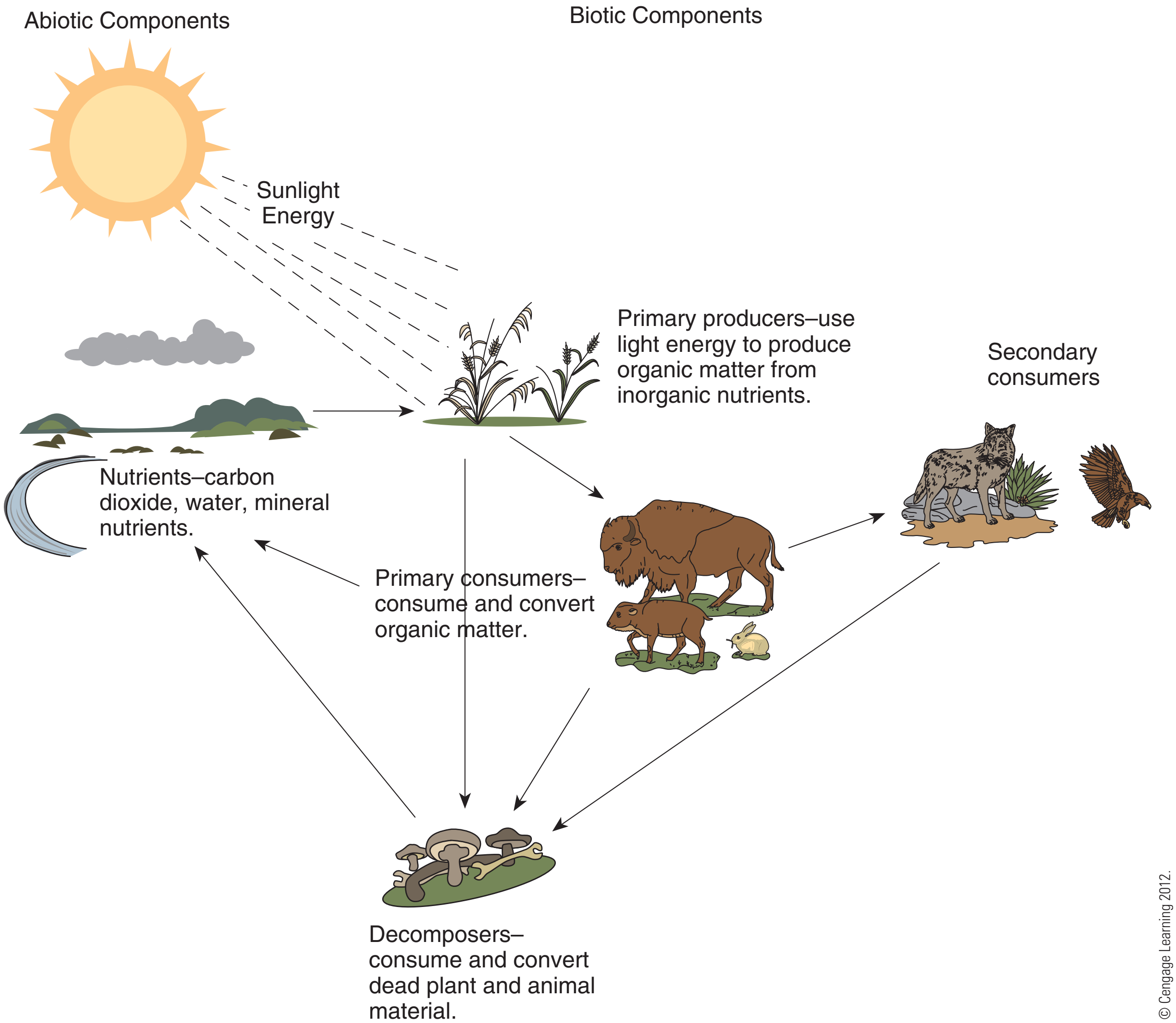


FIGURE 11-1 A grassland ecosystem showing biotic and abiotic components.

Food Chains

Ecosystems have **food chains** that reflect the flow of energy and nutrients. The start of every food chain on our planet is the sun. Food chains begin as green plants or algae, that capture the sun's radiant energy, and convert it into the chemical energy of glucose. Plants are the foundations of most terrestrial food chains and are called **primary producers**. **Consumers** subsequently eat the producers. In the example of the Great Plains food chain, the tall prairie grasses were eaten by jackrabbits or bison, which were the primary consumers. These **primary consumers** were then consumed by **secondary consumers**. The eagle was the secondary consumer of the rabbit, and the wolf was the secondary consumer of the bison. The bison and rabbit are herbivores, whereas wolves and eagles are carnivores. Ultimately, in completion of the cycle of life, even the carnivores die and are decomposed by microorganisms. Their nutrients are then returned to the ecosystem to repeat the cycle.

TABLE 11-1

Important ecosystem services and examples. *Adapted from Costanza et al. (1997).*

Ecosystem service	Examples
Carbon sequestration	Uptake and storage of carbon
Climate regulation	Greenhouse gas regulation; dimethylsulfoxide production that affects cloud formation
Disturbance regulation	Storm protection, flood control, drought recovery, and other aspects of habitat response to environmental variability mainly controlled by the structure of vegetation
Water regulation	Wetlands, watersheds, and aquifers are reservoirs that reduce flooding
Erosion control	Prevention of soil loss by wind, runoff, or other removal processes; storage of silt in lakes and wetlands
Soil formation	Weathering of rock and the accumulation of organic material
Nutrient cycling	Nitrogen fixation; nitrogen, phosphorous, and other elemental or nutrient cycles
Bioremediation	Uptake of nitrogen from manure; sequestration of toxic metals
Biological control	Habitat for predator control of prey species
Wildlife	Habitat, nesting, and survival of migratory and local wildlife
Food production	Crops, nuts, and fruits
Raw materials	Production of lumber and fuel
Genetic resources	Medicinal plants; genes for resistance to plant pathogens
Recreation	Ecotourism, bird watching, sport fishing, hunting, and other outdoor recreational activities

The transfer of energy and biomass from producers to consumers can be described by **ecological pyramids**. Figure 11-2 shows an example for an agricultural system. Plants initially convert only 1–2 percent of the total solar energy into dry matter. At each successive higher level of the pyramid, less energy and biomass is transferred. On average, only about 10 percent of energy and biomass are transferred to the next level. This occurs in part because of the energy and biomass used in metabolism and because of inefficiencies in transfer. Because of the energy loss between levels of the pyramid, most terrestrial and aquatic ecosystems have only three or four levels.

In western societies, meat is a major protein source in diets, and the typical food chain involves grain consumption by livestock and meat consumption by humans. The conversion rate from grain to meat is influenced by the mass of the animal and varies from about 5:1 for cattle to about 3:1 for chicken and 7:1 for pork (Figure 11-3). Those concerned about hunger in light of the world's increasing population have suggested we would be better able to meet the world's nutrient needs if in western societies, such as the United States, humans would directly consume more grain crops as is common in many other societies (Figure 11-4). The human-carrying capacity of the world would be increased if we were herbivores rather than carnivores.

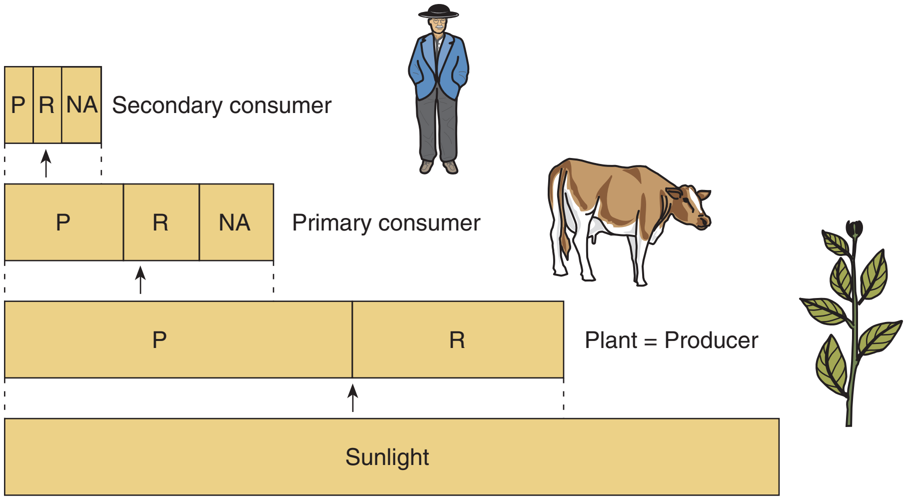


FIGURE 11-2 Energy pyramid for an agricultural system. At each higher level of the pyramid, energy available for production is less. P = production; R = respiration; and NA = nonassimilated energy or waste.

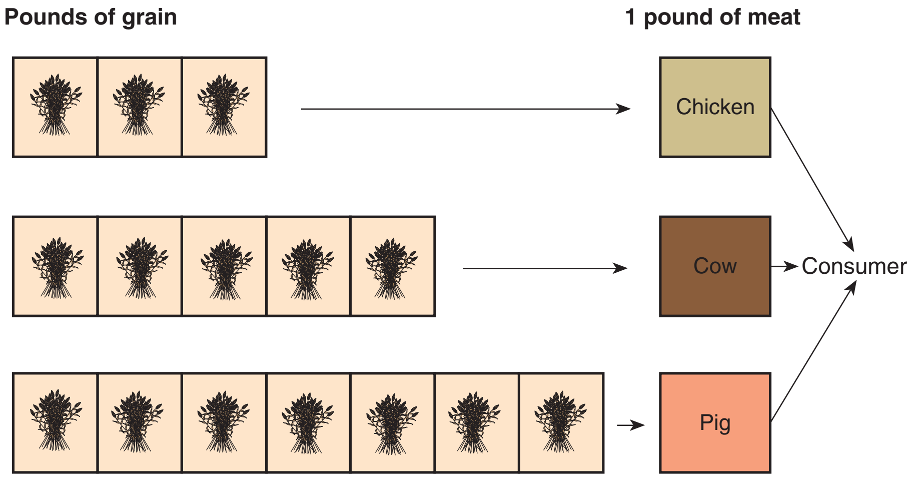


FIGURE 11-3 The efficiency of conversion of grain (energy) into chicken, beef, or pork varies from 3:1 for chicken to 7:1 for pork. For example, it takes 5 pounds (or kilograms) of grain to generate only 1 pound (or kilogram) of beef. Because of energy loss, direct consumption of grain by humans is always more efficient.

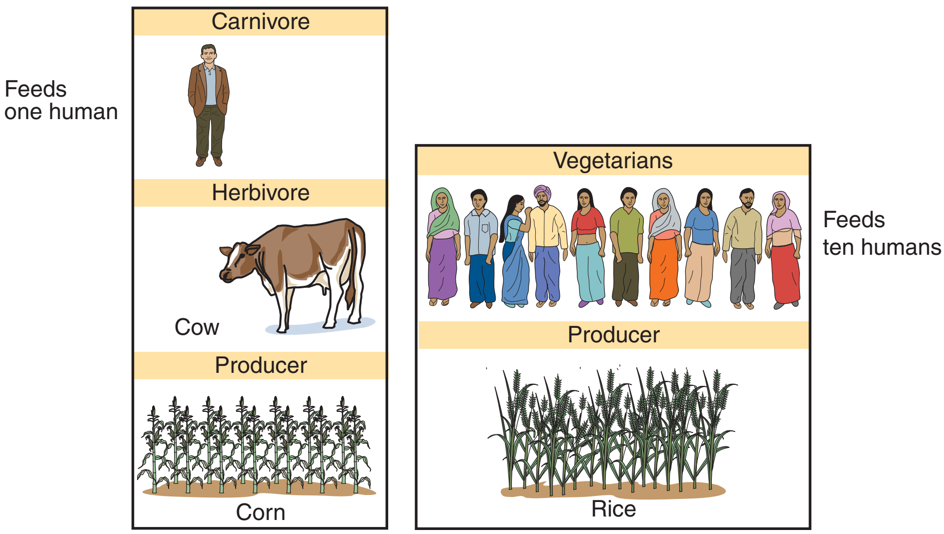


FIGURE 11-4 Energy pyramids comparing caloric production and consumption by meat eaters and vegetarians. Because vegetarians eat rice (the producer) directly, much more energy is available for human nutrition.

Diversity

Natural ecosystems have more biological diversity than modern agroecosystems. This diversity provides for enhanced resource utilization and has the potential to provide stability during times of environmental stress. In other words, there are usually numerous coexisting species that use different resources and have different functions within the **habitat** to which they are adapted. We can see an example of coexisting species in the tallgrass prairie. Tall-growing grasses such as big bluestem, Indiangrass, and switchgrass form a canopy that is full grown in mid-August. Within that tallgrass prairie canopy are short-growing, nitrogen-fixing legumes such as partridge pea, purple prairie clover, lead plant, and Canada milkvetch that flower and set seed beginning in June, when light in the lower portions of the canopy is still adequate. Other nonlegume, broadleaf plants could include wild bergamot, common milkweed, and Maximilian sunflower. Each plant has a unique rooting and nutrient recycling capability. Multiple species provide stability of ecosystem production in the event a disease or drought eliminates or reduces productivity of some species. Simple ecosystems with limited numbers of species at each level of the food chain are more vulnerable to destruction than ecosystems such as the tallgrass prairie with multiple productive species.

Competitive Exclusion: Winners and Losers

In most ecosystems, two species cannot simultaneously occupy the exact same niche. The term **niche** is used to describe the specific range of environmental conditions including air temperature, precipitation, and soils to which a species is adapted within the habitat. The concept of niche is often used to describe the site of plant or animal competition in a specific environment. Plant or animal species will compete for resources, and the species best adapted to the environment's resources such as water, soil nutrients, and light will prevail. The loser in the competition does not necessarily become extinct; it may become adapted to another niche of the landscape.

Plant Succession

Plant succession refers to natural changes in community structure over long periods of time. When agricultural fields are abandoned or natural disasters destroy all existing vegetation, the ecosystem regenerates. This progressive regeneration is

DDT and Biological Magnification

Industrialized food production systems use many synthetic chemicals such as pesticides and insecticides. Energy pyramids can show us how pesticides contaminating the food chain can be concentrated at the highest levels. This is called **biological magnification**, and a classic example is the accumulation of dichlorodiphenyl-trichloroethane (DDT) in food chains (Figure 11-5). People once widely used DDT to control lice and insects such as fleas and mosquitoes that presented health hazards to humans. It was also used to control insects that consumed crops. Extensive use of DDT to control malaria-carrying mosquitoes was credited with saving many lives throughout the world. DDT was effective due in part to its persistence in

(*Continued*)

the environment because it is resistant to breakdown by microorganisms. Unfortunately, DDT accumulation in aquatic systems led to a dramatic reduction in the populations of eagles and other fish-consuming raptors. DDT that first accumulated in small organisms such as plankton at the bottom of the pyramid accumulated in the fat of fish and ultimately ended up in raptors at the top of the pyramid. High concentrations of DDT led to the production of fragile eggshells. The birds accidentally smashed their own eggs during incubation. In addition, humans who consumed fish also accumulated DDT in their bodies. Scientists found DDT in people's organs and in the milk of nursing mothers. In her 1962 book *Silent Spring*, Rachel Carson was the first to alert the public about this environmental crisis. The United States banned DDT in 1973, and eventually much of the world also prohibited its use.

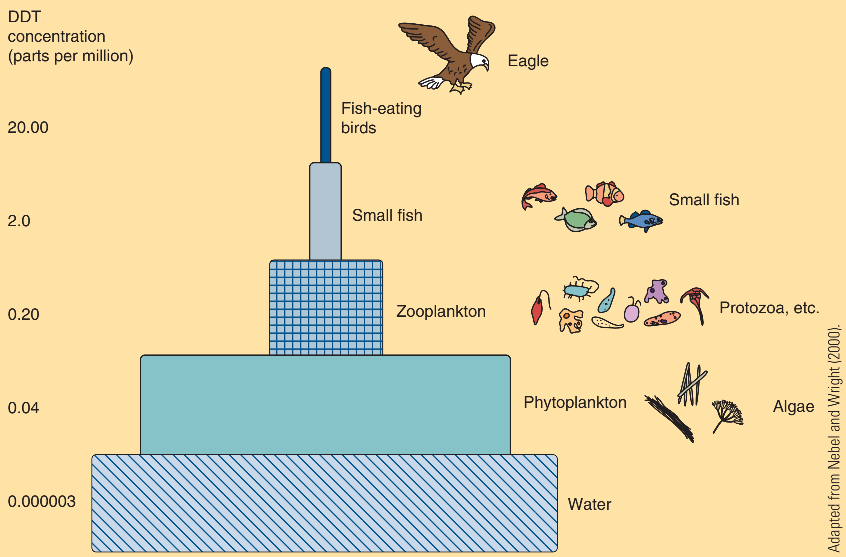


FIGURE 11-5 Biological magnification. The concentration of a pesticide such as DDT, which is not degraded in the environment, is increased up the food chain. The boxes show the relative number of organisms in the ecosystem.

called **ecological succession** and may ultimately result in a diverse and complex community of organisms that are adapted to the resources and environment available at the site. The process may take from 50 to 100 years depending on the climate and species. Let us look at an example of succession in an agricultural setting, an abandoned farm pasture in northern Minnesota that was once continuously grazed by beef cattle (Figure 11-6). The steps in succession are as follows:

1. **0 year.** Before the farmer abandons the pasture, Kentucky bluegrass, red top, and white clover are the predominant vegetation. These plants are present because they tolerate excessive grazing. A small number of tall grasses such as quackgrass, smooth bromegrass, and timothy, as well as some unpalatable weedy forbs (thistle, goldenrod, and yarrow) are present.

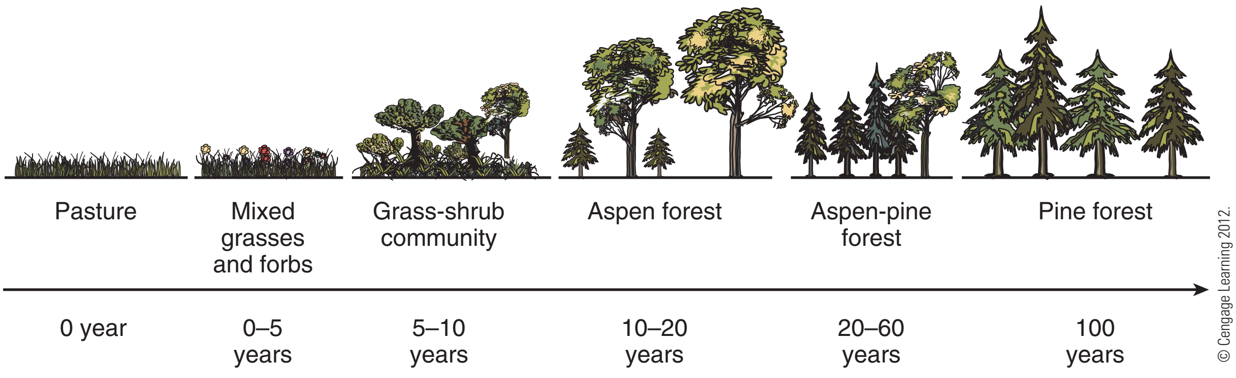


FIGURE 11-6 Succession in an abandoned pasture in the northern United States may take from 50 to 100 years. Overgrazed short grasses are ultimately replaced by pine forest.

2. **0–5 years.** Without grazing, taller grasses such as quackgrass and timothy, and forbs such as thistle, goldenrod, and yarrow express themselves and compete for light. Bracken fern invades from the field edges. The Kentucky bluegrass, red top, and white clover are shaded and lose vigor.
3. **5–10 years.** Seeds of shrubs such as wild raspberry that are spread by birds germinate. Seeds of aspen and white pine that the wind blows into the pasture germinate.
4. **10–20 years.** The fast-growing aspen dominates the vegetation, and the pine continues to grow slowly. The original grasses and forbs die.
5. **20–60 years.** The white pine continues to grow and competes with the aspen for light, water, and nutrients. The aspen begins to die, and white pine becomes the dominant vegetation.
6. **100 years,** white pine becomes the dominant species. Under the pines, wood violets, asters, trillium, and lady slipper develop, as do adapted animal communities.

Together, the concepts of competition and succession of species as features of natural ecosystems explain why modern crop production systems are always faced with challenges related to weed control. The annual and short-lived perennial vegetation established for crop production are usually not natural for that region and are poor competitors. Fields disturbed by tillage for production of crops are colonized by weedy species with high reproductive rates and short life cycles. These weedy species compete with the crops and reduce their yield. Most modern agroecosystems do not allow for competition between weed and crop species and attempt to promote growth of a single species through management and artificial inputs.

Nutrient Cycles

Elements such as carbon, phosphorus, sulfur, and nitrogen continually cycle between the physical nonliving (abiotic) environment and living (biotic) environment. In these cycles, an element may exist as a simple ion, or as a chemical or biochemical compound. In natural ecosystems, nutrient cycles are in balance, and nutrients are not lost from the cycle unless the cycle is disrupted. But in agroecosystems, humans have altered these cycles. We will further explain the concept of nutrient cycling by examining the nitrogen and carbon cycles.

Nitrogen Cycle

Nitrogen (N) is the most abundant element in the atmosphere (78 percent; see Chapter 10) and the third highest constituent in plants after carbon (C) and oxygen (O). A description of parts of the **nitrogen cycle** including human interactions is shown in Figure 11-7. Components of the nitrogen cycle are discussed in the following sections.

The Atmospheric Nitrogen Reservoir Nitrogen in the air is in the form of N_2. It is colorless, odorless, tasteless, and relatively chemically inactive. Therefore, most organisms cannot directly use N_2 from the air. Consequently, nitrogen is the limiting elemental nutrient in most terrestrial ecosystems.

Atmospheric N_2 Inputs into Ecosystems The conversion of atmospheric nitrogen into a stable form that is usable by plants requires energy. There are three pathways by which this occurs.

- **Biological N_2 fixation.** Through the process of biological N_2 fixation (see Chapter 8), atmospheric N_2 is converted to ammonium (NH_4) and ultimately to amino acids that plants can use. The primary form of biological N_2 fixation on the earth occurs through a partnership between a legume such as soybean or alfalfa and a soil bacterium that lives in nodules on the legume roots. Biological N_2 fixation also occurs to a lesser extent through free-living microscopic organisms such as blue-green algae. Nitrogen fixed by legume

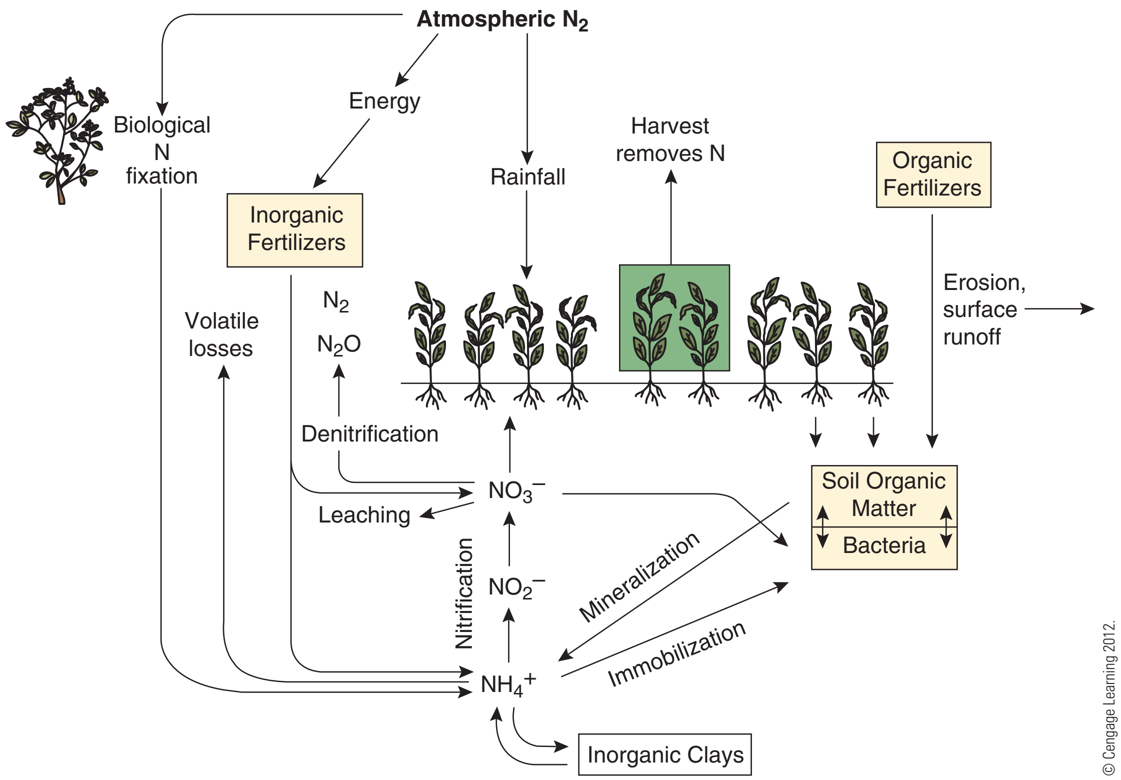


FIGURE 11-7 The nitrogen cycle.

plants using biological N_2 fixation can enter the food chain and is ultimately consumed by animals.

- **Atmospheric fixation.** Lightning that accompanies thunderstorms generates tremendous electrical energy. The reaction of N_2 with O_2 in the atmosphere catalyzed by the electrical energy forms **nitrate** (NO_3^-). This nitrate then falls to the soil with rain and snow, and plants can take it up. The amount of nitrogen that **atmospheric fixation** in natural systems contributes is variable depending on weather conditions. The average atmospheric contribution can be up to 25 pounds of nitrogen per acre (5 kilograms per hectare), depending on location.
- **Industrial fixation.** Although industrial fixation is not a part of natural ecosystems, modern agroecosystems depend on the inputs of nitrogen from this process. Worldwide, this is the largest type of nitrogen fixation. In **industrial fixation**, nitrogen (N_2) from the air reacts with hydrogen under pressure and heat to form ammonia (NH_3; see Chapter 12). Ammonia can be stored under pressure and used directly as a nitrogen fertilizer (**anhydrous ammonia**), or it can be converted to nitrate (NO_3) or other solid fertilizers such as urea [$CO(NH_2)_2$]. Application of industrially fixed nitrogen has greatly increased the productivity of crop production systems but has resulted in a significant imbalance in the nitrogen cycle in terrestrial and aquatic systems.

Plant and Animal Uptake of N Terrestrial plants such as legumes can meet their nitrogen requirements through the process of biological N_2 fixation. Many plant species such as the grasses (corn, wheat, Kentucky bluegrass) rely on nitrogen released from decomposition of soil organic matter or nitrogen supplied by some form of fixation (see the previous discussion). Terrestrial plants take up nitrogen mostly as nitrate and to a lesser extent as ammonium, whether the nitrogen is provided by organic forms, fertilizers, or directly from atmospheric fixation.

Animals and humans eat and digest plant herbage and grain. They use a portion of the plant nitrogen for growth and development. Unused nitrogen is excreted to the soil as urine or feces. Death and decomposition of animals also return nitrogen to the ecosystem.

The Soil Nitrogen Reservoir Soils contain nitrogen in organic and mineral forms. Depending on the organic matter content, soil can contain from 1–10 percent nitrogen. Ammonium (NH_4) and nitrate (NO_3) are the predominant mineral or nonorganic forms of nitrogen in soil. Nitrates are soluble in water and can be found in the soil-water solution. Plants take up nitrogen as either ammonium or nitrate. Ammonium can be loosely attached to particles of soil organic matter and minerals, but nitrate can be leached from the soil into the ground water.

Organic compounds include proteins in the bodies of bacteria and fungi as well as proteins resulting from the decomposition of plant residues, animal residues, and manures. A certain amount of nitrate is also permanently sequestered in the organic portion in the soil. **Immobilization** is the process where nitrate and ammonium are converted to organic nitrogen by soil microbes, making the nitrogen unavailable to plants. The reverse of this process, also performed by soil microbes, is called **mineralization**; the unavailable nitrogen of the organic portion is transformed (mineralized) to nitrate and becomes available to plants. Soil organisms are responsible for this conversion of organic nitrogen to nitrate. **Nitrification** is the process of ammonium being converted into nitrate by soil bacteria. Soil tillage enhances this transformation. This is why grain production

on the virgin native-grass prairie soils during the westward movement of settlers in the 1800s was initially successful. Tillage released nitrogen and other nutrients from the organic matter that had accumulated in the root zone of the native grasses. Today, fertilizers must be supplied for optimum growth, because much of the original nitrogen from the organic matter is gone.

Gaseous Liberation In completing the nitrogen cycle, fixed nitrogen from plants, animals, soils, and fertilizers is converted to gaseous nitrogen forms including dinitrogen (N_2) and nitrous oxide (N_2O). **Volatilization** occurs when gaseous ammonia is lost from the soil surface. While occurring naturally in small quantities, volatilization losses are greatest when nitrogen-containing manures and fertilizers such as anhydrous ammonia



Challenges with Nitrate–Nitrogen

The nitrate form of nitrogen is chemically described as NO_3^--N. It is a negatively charged ion that is very soluble in water and is not attracted to the soil and organic matter fractions. Plants take up and use nitrate for growth and development. It is sold as a fertilizer to supply nitrogen to growing plants and also is formed in the soil when farmers use anhydrous ammonia (NH_3). It is the product of the breakdown of manure from animals and plant residue. In modern crop rotations involving annual crops such as corn, some of the applied nitrogen fertilizers are lost. That, in combination with tile drainage systems, has resulted in considerable nitrate leaching into streams and rivers.

Why is nitrate a problem? Although it is an important nitrogen source for plants, nitrate can be toxic to humans, livestock, and pets when it enters drinking water supplies. The safe drinking water standard for nitrate–nitrogen has been established at 10 parts per million (ppm). Consumption of unsafe levels of nitrate can result in illness and death. It is especially dangerous to pregnant women and small children. When humans ingest nitrate, it goes through the stomach wall and into the bloodstream. In the blood, it binds with hemoglobin, and thus hemoglobin becomes ineffective at carrying oxygen to the body's cells. Hemoglobin turns from bright red to blue-brown. Lips of victims of nitrate poisoning often turn blue, and poisoned babies are called *blue babies*.

In addition to being directly toxic to humans and other animals, nitrate causes extreme environmental degradation. Because it is water soluble, nitrate can easily enter streams, rivers, and oceans. **Hypoxia**, or a deficiency of oxygen, in the Gulf of Mexico has been associated with the excessive amounts of nitrate entering the Mississippi River that drains into the Gulf (Table 11-2). In the Gulf, the nitrates cause excessive growth of phytoplankton and algae and their subsequent decomposition by bacteria, depletes the oxygen in the water. Consequently, the ocean is low in oxygen, so fish and shellfish cannot live. This hypoxia creates a **dead zone** in the Gulf (Figure 11-8).

(*Continued*)

TABLE 11-2

Annual nitrogen inputs to the Mississippi River Basin. *Adapted from Goolsby et al (1997).*

Source of nitrogen	Annual nitrogen input in tons	Annual nitrogen input in metric tons
Commercial fertilizer	6,474,800	5,873,800
Livestock manure	3,804,400	3,451,300
Legumes (soybean and alfalfa)	1,137,500	1,031,900
Atmospheric deposition	564,700	512,300
Human waste	692,000	627,800
Municipal and industrial sources	407,600	369,800
Total, all sources	**13,081,000**	**11,866,900**



FIGURE 11-8 The drainage basin for the Mississippi River with its tributaries and the dead zone in the Gulf of Mexico. This low-oxygen zone results from excess nitrogen flow into the Gulf from the Mississippi River.

(*Continued*)

Producers can utilize practices to minimize nitrogen loss from their cropping systems. These include use of recommended nitrogen-fertilizer rates for a target-crop yield and appropriate application methods. See Chapter 12 for more information on best management practices for nitrogen and nutrient usage.

and urea are applied to the soil surface and not adequately incorporated. Under anaerobic conditions in wet soils and in wetlands, bacteria convert NO_3 to N_2O and N_2. **Denitrification** is the process of nitrate being converted to N_2 under anaerobic conditions by soil bacteria. Burning of nitrogen-containing materials such as grasses and wood converts nitrogen from an organic form and releases it as N_2O and N_2. Nitrous oxide is one of the greenhouse gases, and it accumulates in the atmosphere.

The Carbon Cycle

Life on the earth is based on carbon. Carbon compounds represent the primary form of energy storage on the earth, and the use of fossil fuels is of major interest in the world. Carbon comprises about 45 percent of the dry weight of plants. The **carbon cycle** is shown in Figure 11-9. Components of the carbon cycle are discussed in the following sections:

Carbon Reservoirs Carbon is temporarily stored as carbon dioxide in the atmosphere (it is 0.035 percent of the air). It dissolves in water and ice. It is accumulated as calcium carbonate in shellfish and coral, and as organic carbon in fish. The death and sedimentation of these organisms result in a significant amount of carbon stored in limestone, a prevalent sedimentary rock formed under oceans and other waterways.

Plants were the original source of the carbon found in the coal, oil, and natural gas reserves that our world depends on for energy. These **fossil fuel** reserves formed millions of years ago when our biosphere had a different climate and

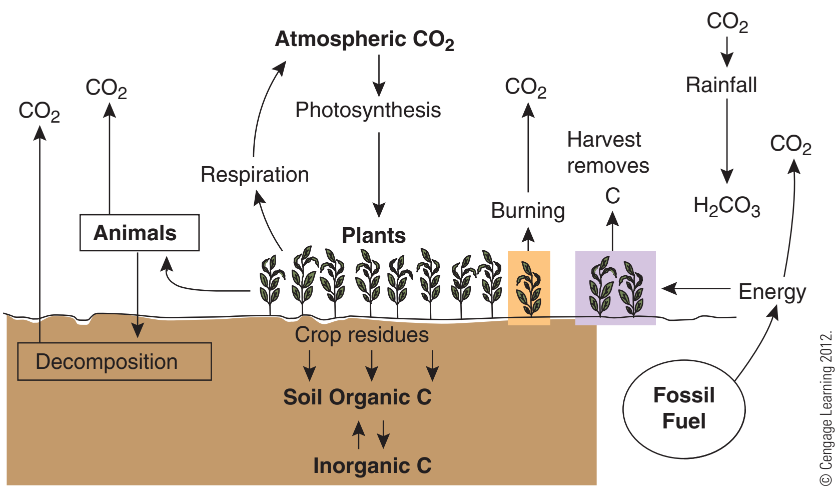


FIGURE 11-9
The carbon cycle.

vegetation pattern. During periods of major climatic change, this vegetation was covered by soil sediment and subjected to intense pressure. Over time, it was converted to fossil fuels. This carbon reservoir is finite and one day will be exhausted.

Soil contains a significant amount of organic matter that is mostly carbon (see Chapter 12). Soil organic matter fractions consist of organisms, recently incorporated and decomposing plant fractions, and the more permanent humus fraction. **Humus** is a complex part of soil organic matter consisting of waxes, lignin, and carbon fractions that are resistant to decay. Cultural practices, especially tillage, greatly affect soil organic matter levels. Soil tillage causes soil organisms to convert a significant amount of soil organic carbon to carbon dioxide.

Agriculture's Role in Carbon Sequestration



Carbon sequestration is the process where carbon dioxide from the atmosphere, through terrestrial photosynthesis, is stored in plant tissues (roots, shoots, leaves, and wood) or in the soil. With recent environmental concerns of increased levels of CO_2 in the atmosphere as a result of burning fossil fuels, carbon sequestration has begun to be investigated as one solution to mitigate future climate change. It is estimated that converting land from the original, native vegetation to cropping in the United States is responsible for the loss of 51 million tons (46 Teragrams) of soil organic carbon (Follet, 2009). Other factors that promote carbon loss are shown in Table 11-3. Consequently, human management of agricultural landscapes has a great impact on carbon sequestration.

Carbon is stored in the soil in several ways: being tightly bound to soil mineral particles such as clays; being in partially decomposed plant residues or humus; and being in plant roots and herbage. Thus, two methods to enhance carbon sequestration include: increasing carbon in vegetation

TABLE 11-3

Agricultural practices that promote carbon loss.

- Fire and burning of crop residues
- Soil erosion by wind and water
- Tillage
- Conversion of land from pasture/cover to tilled land
- Removal of plant residue from fields
- Overgrazing of pastures/rangelands

(*Continued*)

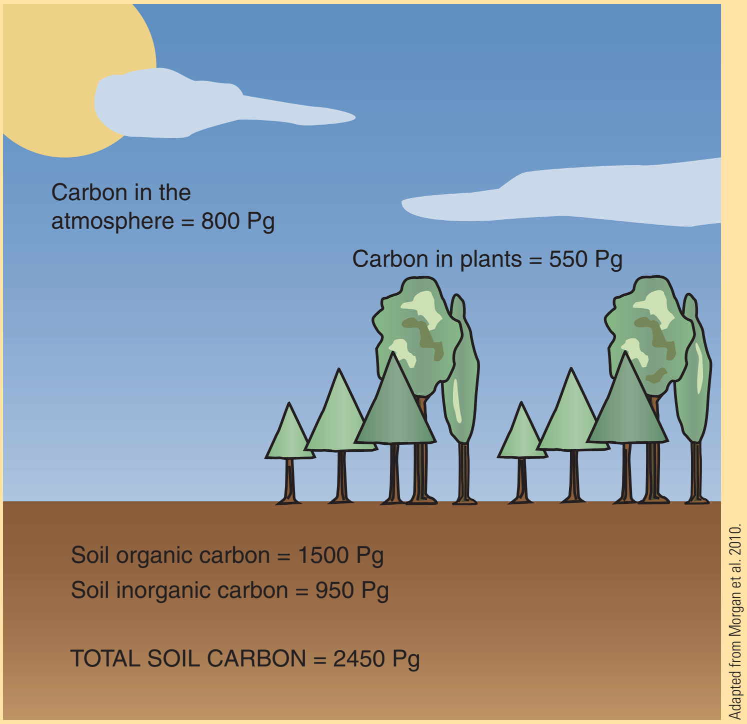


FIGURE 11-10 Most terrestrial carbon is sequestered in soil. Not shown is oceanic carbon, which accounts for 38,000 Pg of carbon. 1 Pg = 1 petagram, equivalent to 10^{15} grams or 42,000 billion tons.

and increasing carbon in the soil. The amount of carbon sequestered in the soil is greater than the amount stored in plants (Figure 11-10) and appears to be the one of the best options to follow to reduce greenhouse gases (Morgan et al., 2010).

Agriculture has changed the amount of carbon sequestered on the landscape, but what is agriculture's role in carbon sequestration for the future? While reverting prime cropping land back to the original native vegetation is not realistic, moving toward a sustainable agriculture can greatly impact the reduction of greenhouse gases. Improving agricultural practices to increase carbon sequestration in the soil can increase the rate of soil organic carbon by 0.04 to 0.45 ton per acre per year (0.1 to 1.0 megagram per hectare per year) (Morgan et al., 2010). Table 11-4 demonstrates agricultural practices that promote carbon sequestration.

(*Continued*)

TABLE 11-4

Agricultural practices that promote carbon sequestration.

- Integration of annual and perennial cropping systems (such as permanent pasture)
- Conservation tillage and no-tillage
- Increase in perennial, biomass crops such as switchgrass
- Green manures/cover cropping that provide year-round ground cover
- Addition of manures and compost (Figure 11-11)
- Management of rangelands/pastures to promote even and regular grazing
- Tree planting and buffer strips on landscapes

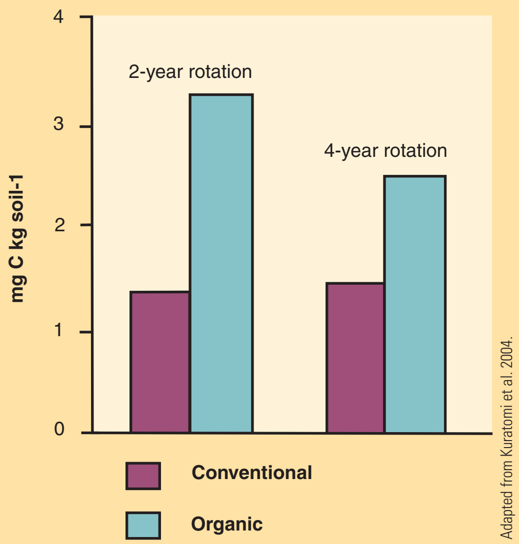


FIGURE 11-11 Amount of active organic matter in conventional and organic cropping systems in Lamberton, MN. The two-year rotation is corn-soybean and the four-year rotation is corn-soybean-oat/alfalfa-alfalfa. The greater amount of organic matter in the organic system is attributed to manure additions.

Carbon Fixation Carbon dioxide and water are the raw materials for the photosynthetic production of glucose (see Chapter 8). **Carbon fixation** is the process of converting carbon dioxide to organic compounds during photosynthesis. Green plants fix and sequester large amounts of carbon. This carbon is stored in leaves, roots, and stems. Glucose provides a carbon structure for many compounds including complex carbohydrates, lipids, proteins, and nucleic acids. A significant amount of carbon is fixed in crop vegetation as well as in unharvested grasslands and forests.

Liberation of Carbon Carbon dioxide in the air is replenished through respiration of carbon compounds by plants and animals, and by burning or decomposition of plant-derived materials such as plant foliage, wood, or fossil fuels. Human activities that affect the amount of permanent vegetation on the earth have a

Carbon Trading

Carbon trading is a relatively new market-based approach to encourage the reduction of the amount of human-generated CO_2 entering the atmosphere. The most common form of carbon trading is the "cap and trade" system in which emitters receive a set amount of carbon credits. In this system, industries that reduce their carbon and greenhouse gas emissions below a set level can sell those credits to other emitters who exceed the limit. The credits allow heavy emitters to avoid fees from the government and incentivizes polluters to upgrade their technology to reduce CO_2 emissions. The World Bank estimates the cost of mitigating one ton of CO_2 is anywhere from $15 to $100. The global carbon market grew more than 5 percent in 2009 to total $144 billion in carbon-offset projects and carbon trading (Kossoy and Ambrosi, 2010). The 2005 Kyoto Protocol encouraged the development of carbon-trading networks. However, a worldwide agreement on carbon reduction has not occurred because several industrialized nations including the United States, China, India, and Brazil did not sign the Kyoto treaty, and no agreement occurred from the climate summit in Copenhagen in 2010.

Carbon and other greenhouse gasses are currently voluntarily traded on the Chicago Climate Exchange in the United States, the only such venue in North America. The emitting participants in the exchange join the cap-and-trade system voluntarily, but are subject to a legally binding contract if they break the terms agreement. The contract requires a stepwise reduction in emissions by 1 percent each year to a total of 6 percent by 2010. Entities like the World Bank are also exploring other alternatives for reducing carbon emissions worldwide by financing emission reduction and carbon offset projects in developing nations. In this way, high emitters can purchase offset credits for certain farming practices that sequester carbon or reduce its emission. These include no-till and reduced-tillage, cover cropping, nitrogen fertilizer reductions, and biogas production and use. Biogas can be produced on livestock farms by the anaerobic digestion of manure. This biogas is made up of methane and carbon dioxide. The methane can be combusted for generating heat or electricity.

large effect on the sequestered carbon. Therefore, destruction of tropical rain forests and other permanent vegetation is a significant concern. Another source of carbon in the air is belching and flatulence by ruminants that ferment plant foods.

Biomes

The prevailing rainfall, temperature, and sunlight patterns on the earth have created unique environments of large, natural ecosystems that contain specific communities of plants and animals. These biotic communities on a global scale are called **biomes** (Figures 11-12 and 11-13). These biomes indicate the natural

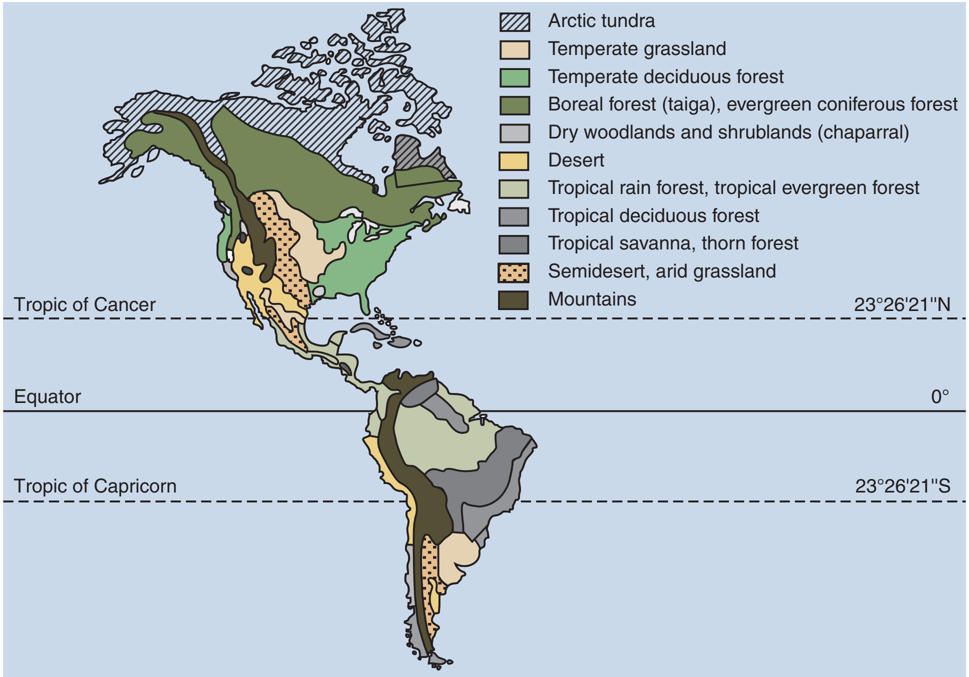
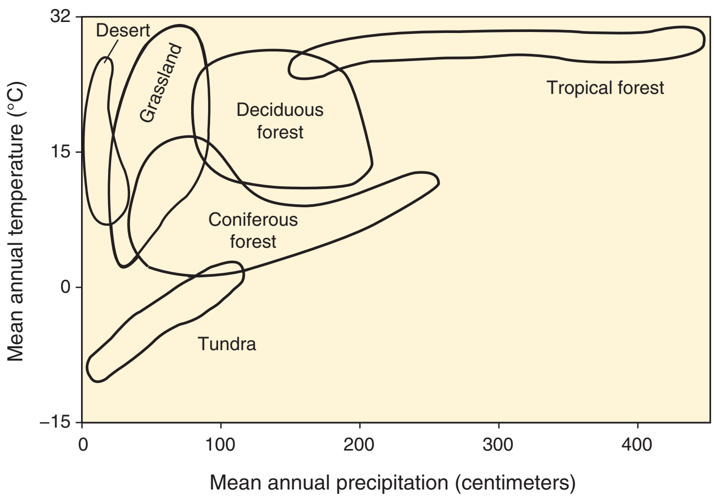


FIGURE 11-12 Biomes are terrestrial ecosystems located in specific environments.



Adapted from Chiras and Reganold (2005).

FIGURE 11-13 Temperature and precipitation ranges for six biomes.

vegetation, much of which no longer exists, but the soils and climate associated with a biome also have a great impact on agricultural food production. The following is a discussion of the major biomes in North and South America.

Tundra

The **tundra** is a large, treeless area in the polar region. It has a short growing season and a very harsh winter environment. Though the surface soil may thaw during the summer, the subsoils are permanently frozen, and this is called *permafrost*. The soil is generally high in organic matter, acidic, and low in fertility.

Small shrubs and the low-growing vegetation of grasses, sedges, mosses, and lichens survive the extended cold winter under a blanket of snow. The combination of poor soil, short growing season, and harsh growing conditions is not conducive to plant growth, and biomass productivity is low relative to the forest and grassland biomes. Disturbances such as mining and oil drilling, which has been proposed for the Arctic National Wildlife Refuge, likely will cause great disruption to this biome.

Forests

Forests at one time occupied more than 80 percent of North American and South American land area. They are the most productive terrestrial biomes. There are temperate deciduous, coniferous, tropical, and mountain forests, each with distinct tree species. In the eastern United States and southern Canada, where rainfall is generally high, the deciduous temperate forests consist of oak, chestnut, hickory, and maple. Bordering the deciduous forest to the north is the northern coniferous forest. The predominant trees include white and red pine, spruce, and fir. In some wetlands, tamarack—a deciduous conifer—grows. During settlement, wood from these forests was the raw material for building industries and cities. Once forests were cut, the land was cleared for agricultural uses such as grazing and cropping. Though old growth remnants still remain, many of the original forests have been lost.

In the western United States, coniferous forest grows over the unique soils and topography. Rainfall ranges from 15 to more than 40 inches (38 to more than 102 centimeters) annually. In some areas, precipitation occurs mostly as snow. A forest of Douglas fir, coastal redwoods, ponderosa pines, and red cedars is located in the Cascade Mountains of the Pacific Northwest and extends into California. Interior forests of ponderosa pine, lodge pole pine, and Douglas fir exist in Idaho, western Montana, western Wyoming, and western Nevada. In some areas, conifers are mixed with aspen. In contrast to eastern forests, more remnants of these original forests remain.

Tropical rain forests in Central and South America have a diversity of plants and animals. As their name implies, they experience high humidity and high rainfall. The plant, animal, and insect species are diverse and numerous. Many species such as frogs, colorful birds, insects, and monkeys occupy the forest canopy. The forest has trees of varying height with hanging vines intertwined so that little light reaches the forest floor. These tropical forests are now being extensively studied as a source of medicinal plants and rare plant and animal species. Like the temperate deciduous and coniferous forests two centuries earlier, tropical rain forests are now being cleared for settlement, agriculture, wood, and mining. The result is a dramatic loss in animal and plant species. It is estimated that unless significant intervention occurs, the tropical rain forest and many of its species will largely be extinct within this century.

Grasslands

Grasslands are found in both North America and South America. In South America, they are called the *pampas*. Prior to European settlement, the Great Plains of North America were perennial grassland prairies (Figure 11-14). The species there were greatly influenced by the amount and pattern of precipitation. The grasses were primarily warm-season types. Warm-season grasses make their maximum growth during the warm, summer months. Short grasses predominated in the drier western region, and in the eastern part of the grasslands, tall grasses dominated. At the interface of the region was a mixture of tall and short grasses, shrubs, and short stature legumes. Within the short-grass prairie, grass species included little bluestem, blue grama, buffalo grass,



FIGURE 11-14
Horses graze on rangeland that is representative of the temperate grassland biome.

and side oats grama. In the tallgrass prairie, grasses included big bluestem, little bluestem, switchgrass, and Indiangrass. In both tallgrass and short-grass prairies, forbs and legumes such as prairie clover, leadplant, and shooting star bloomed in the spring and summer. Buffalo grazing and fire were important for maintenance of this ecosystem.

To the pioneers who first encountered the tallgrass prairies on their journeys west through Iowa, Illinois, and Minnesota, the prairies appeared as a moving sea 12 feet (3.7 meters) tall that swallowed horses and wagons. Trees existed only along waterways. The tallgrass prairies also had thick, deep, root systems and rich, high-organic-matter soils. Since settlement of this region, much of the original grassland has been tilled and replaced with crops. The rich soils of the tallgrass prairies are the foundation for the Corn Belt's corn-soybean rotation. Toward the west, wheat is grown with and without irrigation, and many introduced, temperate grasses are used for grazing. Large portions of the western and southern prairies are still used for grazing. Today, only small remnant prairies remain from the great grasslands. However, efforts are underway to promote native plantings through federal- and state-supported programs.

Deserts

Deserts develop when annual rainfall is between 5 and 10 inches (13–25 centimeters), and they typically have extreme daytime temperatures. The distribution of precipitation is usually not uniform during the year. It often falls only during the winter months or in cloudbursts during the other seasons. Deserts have vegetation that is specially adapted to



FIGURE 11-15
The desert of the southwestern United States is typical of the desert biome. Only plants that are adapted to low-rainfall conditions and high temperatures grow in these regions.

survive (Figure 11-15). These include cacti, creosote bush, mesquite, and sagebrush, all of which have thick or leathery cuticles and water-storage tissue in stems and leaves. Also, some winter-annual desert plants persist by flowering in the winter and spring during wet periods, and then setting seed before the onset of the dry period. Because of the extreme conditions, most desert regions have not been used for agriculture unless water can be supplied through irrigation. An example of the use of a desert for agricultural production is the Imperial Valley of California. Water transferred via aqueducts from the Sierra Mountains has transformed the desert into a major site for cotton and vegetable production.

Agroecosystems

Agroecosystems are ecological systems that humans manage to produce food, fiber, or other agricultural products of economic value. Cultivated cropland and managed pastures now occupy more than 40 percent of the earth's land area. Well-managed agroecosystems are critical to supply nutrition and shelter to the ever-increasing world population, which is almost seven billion people today and is expected to reach nine billion by 2050. Over the past 50 years, worldwide grain production has increased by almost 1 trillion tons (907,000 megatonnes) per year (Figure 11-16).

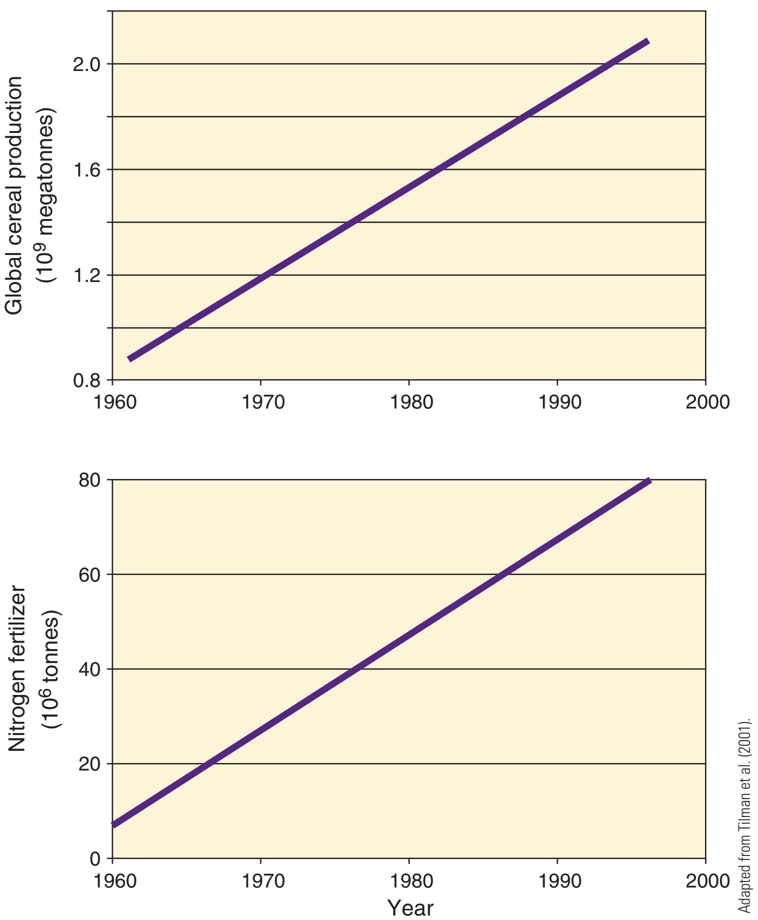


FIGURE 11-16
Trends in global cereal production and fertilizer use. 1 megatonne is about 1 million tons.

This increased land use and food production has been associated with the development of new crop varieties and expanded use of technologies such as fertilizers, pesticides, and irrigation. The use of technology to enhance global food production has been described as the **Green Revolution**.

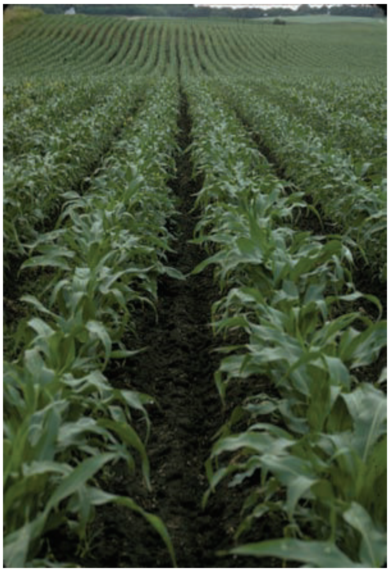
In agroecosystems, ecosystem diversity, services, and functions have been replaced with simplified systems relying on technology as well as mechanical and biological inputs for productivity. Therefore, modern agriculture has been called high-input agriculture. In economic terms, modern farms can be considered industrial factories producing raw materials for the food industry. For profitability, minimizing production costs is critical. This is **industrialization of agriculture**. Because this approach is commonplace, it is also called **conventional agriculture**.

Types of Agroecosystems

Different types of agroecosystems are practiced in the United States. We will discuss examples of crop-based and animal-based systems practiced in the northern United States.

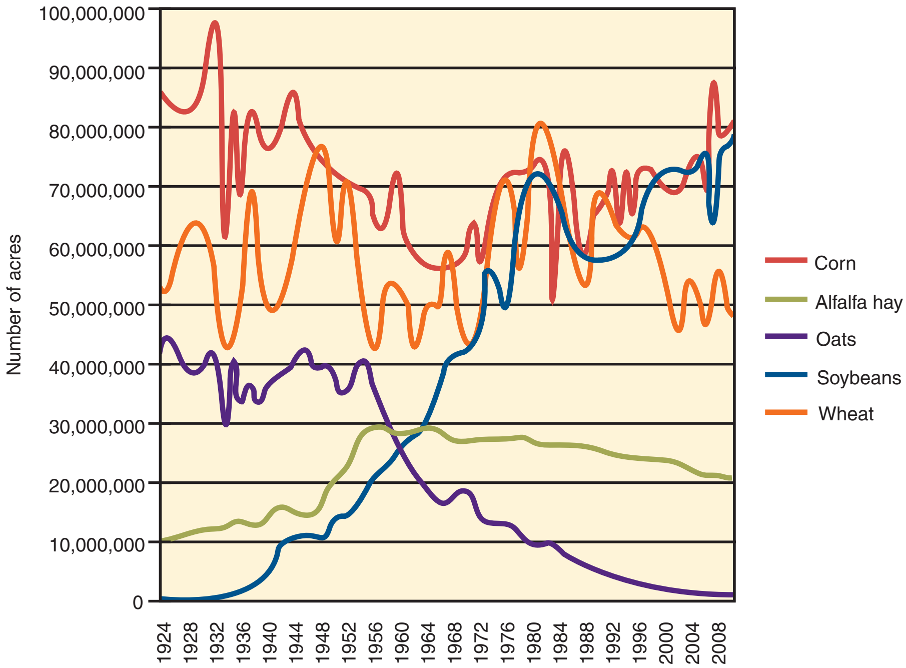
Corn-Soybean Rotation

Figure 11-17 shows the corn component of the corn-soybean rotation that is now planted on more than 100 million acres (40.5 million hectares) in the United States. Production of corn and soybean has displaced other crops on the landscape (Figure 11-18). In this system, corn and soybean are grown as annuals, planted in the spring and harvested in the fall. These crops have been bred for maximum grain productivity in the specific region in which they are grown. The harvested grain is sold and then removed from these farms, which usually have no livestock. Synthetic fertilizers supply essential nutrients, and synthetic pesticides provide weed (herbicides) and insect (insecticides) control. Vegetation grows on the landscape for only a portion of the year. Only crop residues cover the soil surface from October to May. This system typically suffers loss of soil from water erosion and can contribute herbicides and fertilizers to wetlands and waterways.



David L. Hansen, University of Minnesota.

FIGURE 11-17
The corn-soybean annual crop rotation is the predominant agroecosystem in the Upper Midwest.



USDA-NASS (2010).

FIGURE 11-18 Corn and soybean are the predominant crops grown on Midwest landscapes. The acreage of all other crops has decreased since 1920.

Animal-Based Agroecosystems

An animal-based agroecosystem that is still widely practiced in the northern United States and Canada is:

Corn → Soybean → Alfalfa → Alfalfa → Alfalfa

In this system, corn and soybean are each grown for one year, followed by three years of alfalfa. Then the field goes back to corn again. Alfalfa, a perennial, grows continuously for three years (see Chapter 13). It is fed to dairy cattle on the farm, and their manure fertilizes corn and soybean crops. Alfalfa is also used as a green manure crop and supplies nitrogen to the following year's corn crop, reducing nitrogen-fertilizer inputs. Production of three years of alfalfa also controls annual weeds and reduces herbicide input. This system is less dependent on fertilizer and herbicide inputs than the corn-soybean system, but off-farm inputs are still required. These include crop seed, herbicides, fertilizer, and dairy herd costs such as breeding and veterinary. Milk and soybean are sold off the farm. Soil and nutrient loss still occurs but at a lower rate because the alfalfa provides year-round soil coverage, and nitrogen from alfalfa replaces some fertilizer.

How Do Ecosystems and Agroecosystems Differ?

Agroecosystems that are managed to produce food and fiber differ from natural ecosystems (Table 11-5).

TABLE 11-5

Summary of differences of ecosystems and agroecosystems.

	Natural ecosystems	Agroecosystems
Diversity	High	Low—may be monocultures
Inputs	None	High—including fertilizers, pesticides, labor
Management	None	High—human input
Breeding	None—except for natural selection	High—many years of breeding
Nutrient loss	None—nutrients recycle	Some—losses of soil and nutrients

Diversity

Most widely used agroecosystems lack plant- and animal-species diversity. In the world, three crops (wheat, rice, and corn) supply over three-quarters of our food. In much of the midwestern United States, corn and soybean are the only crops grown on individual farms. Like plant species, animal species are also limited in modern agroecosystems. In North America, cattle (dairy and beef), hogs, and chickens are fed mostly corn and soybean, and they supply 90 percent of the meat that consumers purchase.

Plant and Animal Breeding

Humans have developed improved varieties of most crops to increase productivity of economically valuable traits. These traits include selecting for grain yield and quality (corn, soybean, wheat, and rice), forage yield and quality (alfalfa and corn), and fiber yield and quality (cotton). Selection for crop disease and insect resistance is also an important approach to increasing yield and quality. Crops are selected for uniform maturity, uniform grain size, and dry down and lodging (tipping over) resistance to facilitate harvesting. A dramatic example of successful plant breeding was the development of rust-resistant, semidwarf wheat adapted to the soils and climate of Mexico by Norman Borlaug (1914–2009), a leader of the Green Revolution. These new wheats had twice the yields of traditional varieties. Robert Chandler at the International Rice Institute in the Philippines achieved a similar success with semidwarf rice that was insect and disease resistant. The most recent plant improvement innovations include the development of genetically modified plants with herbicide tolerance and insect resistance. Chapter 9 provides more details about improving plants through plant breeding and genetic engineering.

Livestock such as chicken, beef, and turkey has also been selected to provide high rates of gain and efficiency, and dairy cattle have been selected for enhanced milk production. Chicken is an excellent example of livestock that has been improved by breeding. Before World War II in the 1940s, the typical chicken meat came from older hens and young roosters that were left over from

the egg-laying industry. Chicken meat was expensive, and availability was very seasonal. Today, chicken consumed at home and in fast-food restaurants is from specially developed broiler breeds selected for feed conversion efficiency and high rates of gain. They are processed for meat products just eight weeks after hatching. Chicken is now available year-round and at a low price. Likewise, swine and beef are selected for uniformity in meat characteristics to enhance processing and marketing efficiency.

Human Ingenuity

Since the early days of hunting and gathering, humans have been manipulating natural ecosystems. Technological advancements have always been applied to agriculture, and they have gained momentum since the Industrial Revolution in the 1800s. In addition to significant efforts in plant improvements, humans have made other innovations to increase plant and animal productivity and the efficiency of food production. Examples include the employment of precision agriculture to account for variation in the field to optimize fertilizer and pesticide usage, controlled ration balancing for livestock feeding, the development of irrigation systems, the advances in machinery to optimize establishment and harvest of crops, and the development and use of vaccines for protection of animals against disease.

Concentration of Livestock

Meat, milk, and egg production occurs mostly in confined animal feeding operations (Figure 11-19). Confinement rearing of livestock allows for increased efficiency of livestock feeding and production. It ultimately lowers food prices because:



Larry Rana, USDA.

FIGURE 11-19 Confinement raising of chickens in Florida.

(*Continued*)

- Capital costs of buildings and equipment are spread over a large number of animals.
- Rations based on the cheapest ingredients are standardized to meet the nutritional needs of a large number of animals of similar weight and stage of development.
- Animals can be uniformly treated with medicine for disease and other pests and with growth-promoting agents.
- Because animals are confined, nutrients are used mostly for growth and production, rather than exercise.
- The product—whether meat, egg, or milk—can be adjusted to be of uniform size and quality.

Livestock production facilities can be located near transportation facilities or processing facilities. The concentration of livestock in confinement feeding facilities has posed some challenges related to animal health, human health, and environmental quality. Some of these issues can be dealt with through improved management practices. Here are some of the issues.

- Large numbers of animals raised in close proximity present an opportunity for rapid spread of infectious diseases. Preventive medications such as antibiotics are often used.
- Animals are confined in small cages or in feedlots with a minimal amount of space for natural movement or social interaction. Some people feel this industrialization of animal production is an animal welfare concern.
- Manure and urine excrement is concentrated in a small area, making disposal challenging. Manure is often stored in lagoons that can affect surface- and well-water quality. For example, in 1995 in North Carolina, a leaking lagoon resulted in the discharge of 25 million gallons (94.6 million liters) of liquid manure into the nearby New River. This killed more than 10 million fish, destroyed recreation in the river, and fouled drinking water. Leaching of nitrate from concentrated manure application or leaky lagoons can contaminate groundwater, leading to problems of nitrate (NO_3) poisoning.
- Air quality is degraded. Pollutants such as hydrogen sulfide (H_2S), methane (CH_4), ammonia (NH_3), and particulates generated by manure production and storage affect the health of animals, farm workers, and nearby residents. Inhalation of these pollutants can cause asthma, chronic lung disease, and brain and nervous system dysfunction.

Nutrient and Energy Inputs and Losses

For high levels of crop production, nutrients are added through fertilizers, herbicides are used for control of unwanted plants (weeds), and insecticides are used to control insects. Energy is used for mechanical operations such as tillage, planting, and harvesting. Other energy and resource inputs include irrigation to grow crops in arid environments and drainage of wetlands to create upland environments. Energy is harvested with removal of crops, but the inputs and outputs are not always in equilibrium.

Modern agroecosystems sometimes lose significant soil resources essential for their viability. The soil used for productive agricultural systems is the upper biochemically active portion of the earth's crust. The topsoil has more organic matter, microorganisms, and mineral content than the subsoil. Topsoil is lost through the process of erosion (Figure 11-20). **Erosion** is the detachment and movement of soil minerals and organic matter by wind and water. Since the earth's formation, natural erosion has resulted in the leveling of mountains and the carving of valleys and canyons in the earth's surface. Modern agriculture has resulted in accelerated rates of soil erosion that are sometimes 100 times greater than the rate of soil formation (see Chapter 12). The estimated annual rate of soil loss from water and wind erosion from all croplands and grazing lands in the United States is more than 5 tons/acre/year (22 metric tons/hectare/year). Erosion occurs when the soil is disturbed and exposed by construction, tillage, traffic, or excess grazing. Soil erosion reduces soil organic matter and mineral nutrients, changes physical properties of the soil, reduces habitat for organisms, and reduces the soil's ability to hold moisture.



Tim McCabe, USDA-NRCS.

FIGURE 11-20
Soil erosion from a field in early summer. Because of the lack of ground cover early in the growing season, fields with crops such as corn are subject to extensive soil erosion by water.

Risks of Simplified Agroecosystems

The simplified food chain that is used in modern agroecosystems is vulnerable should production of the plant or animal components near the base of the chain be disrupted. This could occur in modern-day soybean and corn crops that are planted over large acreages. Some historical examples of the consequences of ecosystem simplification follow.

Irish Potato Famine

The Irish potato famine occurred in nineteenth-century Ireland. At that time, the Irish depended on the potato as their primary source of nutrients. Only a few varieties of potatoes were grown over large acreages. A fungus originating in the Americas reached Ireland in the 1840s and rapidly destroyed the potato crop and any stored potatoes. Because very few other crops were grown as part of the food web, the destruction of the potato crop resulted in the starvation of more than one million Irish people and the migration of another million.

Wheat and the Dust Bowl

The **Dust Bowl** occurred during the 1930s in the southern Great Plains of the United States. It resulted in the loss of millions of tons of top soil, as well as the social and economic devastation of the region (Figures 11-21 and 11-22). About 30 percent of the population migrated from the region. Those remaining were left with a poor soil resource for farming, and many became financially poor. The Southern Plains are normally an arid region subject to periodic drought. Prairie grasslands are the native vegetation. These grasses tolerate drought and have a fibrous root system that holds the soil. This region is best suited to livestock grazing



FIGURE 11-21 The center of the Dust Bowl was the Five Corners region in the Southern Plains. High temperatures and below-normal rainfall caused widespread drought during the 1930s from North Dakota to Texas.



FIGURE 11-22
A large dust storm ("black roller") moves across the land during the Dust Bowl.

rather than crop planting. The Dust Bowl was a direct result of intensive tilling of much of the native prairie grasslands without leaving protective soil residue and the planting of wheat during the 1920s, a period of above-average rainfall and high wheat grain prices. Unfortunately, when dry conditions recurred in the 1930s, the wheat died, and the exposed soil blew away in large dust storms that often lasted for days. Dust from the Great Plains was deposited as far away as Chicago, Illinois, and Washington, DC. More than a foot of soil was lost from some areas in the region.

One innovation that spread as a result of the Dust Bowl was a plow invented by Charles Sherwood Noble in 1935. The Noble blade plow undercut existing vegetation at the roots while leaving plant residue on the surface to protect the soil from erosion. The Noble plow was quickly adopted as an alternative to the moldboard plow, particularly in dryland regions such as the southern Great Plains.

Wetland Drainage

Fresh and saltwater wetlands are natural features of our landscape that provide critical services to the ecosystems (Figure 11-23). They provide habitat for wildlife such as songbirds, ducks, and muskrat. They provide temporary storage for water from runoff and storms; they store carbon; they also reduce nitrogen and phosphorous in waters. Unfortunately, in modern agroecosystems, the value of wetlands has not always been appreciated. Wetlands have been considered impediments to agriculture and travel, as well as the source of blackbirds that consumed crops, and the source of mosquitoes that preyed on humans and livestock. Of the more than 225 million acres (91.1 million hectares) that were present before settlement in the lower 48 states, less than half are left today (Figure 11-24). Much of the original wetlands are now farmed. Wetlands are still disappearing at a rate of about 50,000 acres (20,000 hectares) per year. Initial drainage occurred through the use of ditches and trenches dug by men and horses, and then large steam shovels. The first drainage tiles were clay. Today they are plastic, and their depth is adjusted using laser levels.

Wetland loss through drainage has impacted most states. California and Ohio have lost at least 70 percent of their original wetlands. The loss of wetland



FIGURE 11-23
An aerial view of wetlands in Butte County, California. Wetlands play a critical role in our agroecosystems. They provide habitat for wildlife and temporary storage for water from runoff and storms. They also store carbon and can reduce nitrogen and phosphorous in waters.

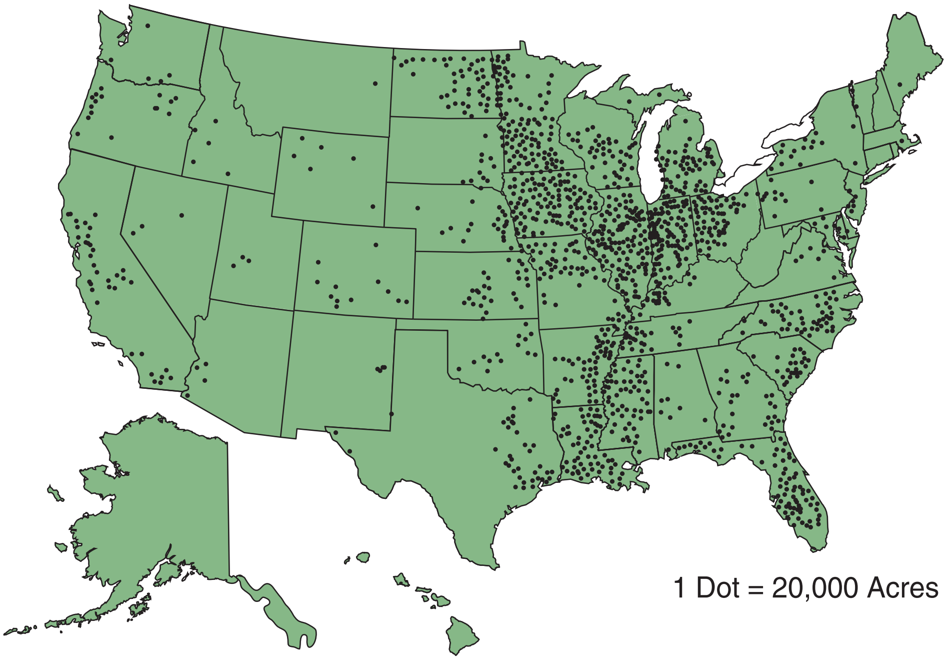


FIGURE 11-24
Extent and location of artificially drained agricultural land in the United States, 1985. An estimated 87 percent of the wetland losses from the mid-1950s to the mid-1970s was due to agricultural drainage. 1 dot = 20,000 acres = 8,094 hectares.

in the prairie pothole (circular depressions left by retreating glaciers) region of Minnesota, Iowa, and the Dakotas is indicative of the significance of the problem. In the mid- to late-1800s, a large part of the prairie pothole wetlands was drained for farming by using ditch systems and clay drainage tiles. This activity coincided with the destruction of most of the native prairies for crop production. Though the rate of wetland drainage has slowed, new drain tiling is consuming about 100 million feet (30.5 million meters) of pipe per year in Minnesota alone.

The tile drainage system that improves the efficiency of farming provides a conduit for rapid percolation of sediment, fertilizers, and pesticides to ditches and

waterways (Figure 11-25). In the southern portion of Minnesota, these waterways ultimately flow into the Minnesota River, a tributary of the Mississippi. The hypoxia problems in the Gulf of Mexico have been associated with the fertilizer losses that move through the drainage system in Minnesota and other Corn Belt states. Other issues include the dramatic loss in duck- and goose-hunting opportunities and the increased frequency of floods along the waterways due to the loss of temporary storage provided by wetlands.

A Sustainable Agriculture

Modern conventional, industrialized agriculture has been very effective at providing large quantities of inexpensive food. However, many scientists are concerned this benefit may be short-term because of the loss of soil resources and degradation of the environment by synthetic fertilizers and pesticides. In addition, concentration of livestock production may not be profitable overall because of environmental issues. It is important for the future that we consider sustainable agricultural practices. In the context of the ecological principles discussed in this unit, a **sustainable agriculture** should have the following characteristics:

1. Maintenance of the soil, water, and air resources for future generations. Farming practices should be in harmony with nature and facilitate ecosystem services. The earth's land resource is not infinite; farmers should be stewards of the land with the goal of passing this resource to future generations. Likewise, a sustainable agriculture should not degrade water and air resources. Agriculture may actually have a role in the remediation of degraded soil, air, and water.
2. Accountable and profitable production of food, fiber, or energy to meet societal needs. Sustainable farming is a critical occupation for the future of our societies. It should therefore be profitable for farmers who are good stewards of the land. A sustainable agriculture should be economically accountable for the consequences of environmental degradation.

Therefore, sustainable agricultural systems of the future will likely be multifunctional in providing both environmental and economic benefits. This will require development of systems that consider strategic use of all features of the landscape. For example, annual crops such as corn and soybean will be strategically placed in



USDA-NRCS.

FIGURE 11-25
An aerial view of a recently installed tile drainage system designed to rapidly remove moisture from the landscape. About 60,000 feet (18,000 meters) of plastic tile were installed on 160 acres (65 hectares). The ultimate outlet of tile drainage systems is to manmade ditches or natural waterways.

areas where they grow best and have the least effect on the environment. Likewise, perennial biomass and grain crops would be grown in portions of the landscape where they can produce valuable products while protecting the environment.



SARE

Numerous organizations have been established throughout the United States to promote a sustainable agriculture. The Sustainable Agriculture Research and Education Program (SARE) was established in 1988 as a part of the USDA–National Institute of Food and Agriculture (then known as the *Cooperative State Research, Education, and Extension Service*). SARE's mission is to advance farming systems that are profitable and environmentally sound and that have a positive impact on rural communities. SARE funds research, professional development, and education to improve agricultural systems. The Sustainable Agriculture Network disseminates information about sustainable agriculture. A unique component of SARE's funding program is its support of farmer-led research aimed at solving practical agricultural problems. The SARE funding program has enabled farmers to conduct onfarm research. Recent projects have included building better grazing systems in New York, testing forage systems for goats in Alabama, developing best management practices for potato growers in Idaho, advancing organic agricultural education in Georgia, and using renewable energy on farms in Massachusetts. To find out more about SARE programs and opportunities, see <http://www.sare.org>.

Review Questions

1. Define ecology.
2. What are the components of ecosystems?
3. What are some of the different functions that ecosystems provide?
4. What are agroecosystems, and how do they differ from ecosystems?
5. Describe the flow of energy in a food chain.
6. What are ecological pyramids, and how do they help us understand biological magnification?
7. What are biomes? Describe several biomes.
8. What do the nitrogen and carbon cycles show us about the movement of nutrients through ecosystems?
9. Describe inputs and potential losses from the nitrogen cycle.
10. Describe environmental problems that are associated with human agricultural activities.
11. What is sustainable agriculture?

Critical Thinking

1. Go to a website or newspaper and locate an article that describes an agricultural production practice. What is the product of that system? Does the system have any environmental impact? If these issues are not discussed, are there any to consider?
2. Do a study of the Dust Bowl disaster and review the significant impact on humans, animals, and the environment. Could the Dust Bowl happen again? Why or why not?
3. Hypoxia is a worldwide problem. Identify areas around the globe where hypoxia is a problem. How can we reduce or eliminate the problem?
4. The confinement of animals for meat and egg production is commonplace in the United States. If you agree with the concerns about confinement feeding, what are the options? If you do not agree with the concerns, state why.
5. Your ecological footprint is the amount of land and resources needed to support you. Go to a website that calculates your ecological footprint—for example, <http://myfootprint.org/>—and take the quiz. How do you compare to the average citizen in the United States? How about the average citizen in the world?

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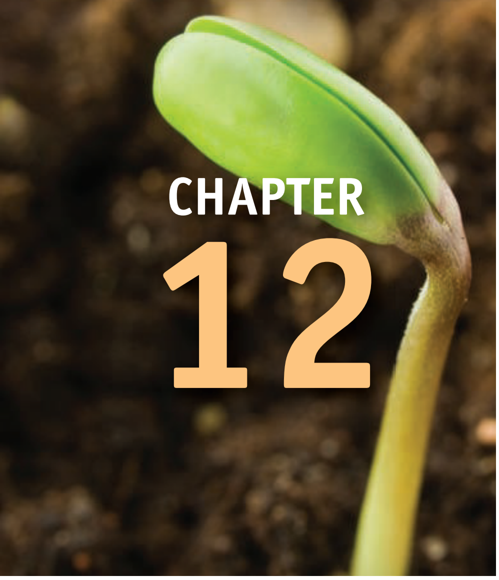
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CHAPTER 12



Soils





Key Concepts

- The soil is an essential resource for the production and growth of plants and crops.
- Soils are a mixture of minerals, organic matter, organisms, pore space, liquids, and gases.
- Soils are formed over long periods of time by the action of chemical, physical, and biological factors on sedimentary, igneous, and metamorphic rocks.
- A soil profile is a vertical section through the soil extending from the surface to the unweathered rock beneath.
- Organic matter is a source of nutrients for plants, aids soil aggregation and structure, and provides storage for water.
- Soil properties affecting plant growth include texture, structure, and chemistry.
- The ability of a soil to supply important chemical nutrients or essential elements is described as soil fertility.
- Soil texture describes the fineness or coarseness of a soil and is determined by the proportion of specific soil particles: sand, silt, or clay.
- Organic and inorganic fertilizers are used to supply nutrients to plants.
- Erosion is the accelerated loss of soil through the action of wind or water. Conservation tillage and permanent vegetative covers can minimize erosion.

Key Terms

carbon:nitrogen ratio (C:N ratio)
cation exchange capacity
Crop Productivity Index (CPI)
essential element
fertilizer
field capacity
gravitational water
horizon
inorganic fertilizer
Mollisol
organic fertilizer
organic matter
parent material
permanent wilting point
pore space
profile
salinity
soil
soil fertility
soil texture
tilth
topsoil

Introduction

The **soil** is a medium for the production and growth of plants and crops. It provides an environment for plant roots to grow and absorb the water, oxygen, and nutrients essential for plant development and growth (Figure 12-1). The ability of a soil to supply important chemical nutrients or essential elements is described as **soil fertility**.

Soils provide anchorage for plants. Roots growing in soils support the upright stem and leaf structure of a plant. Roots of most crop plants are often found in the top foot of the soil, where air, water, and nutrients are ideal for growth (Figure 12-2). Some plants like alfalfa can grow roots as deep as 30 feet (9.1 meters) into the soil in search of nutrients.

Soils are ecosystems. Soils contain numerous organisms that interact including plants, bacteria, fungi, insects, and invertebrates. As part of this ecosystem, soils provide essential services such as carbon sequestration and the sequestration of toxic chemicals.

Finally, the soil is also valuable as a site for recreation and as a foundation for buildings and roadways (Figure 12-3). Unfortunately, human construction and recreational activities often result in changes to and destruction of soils.

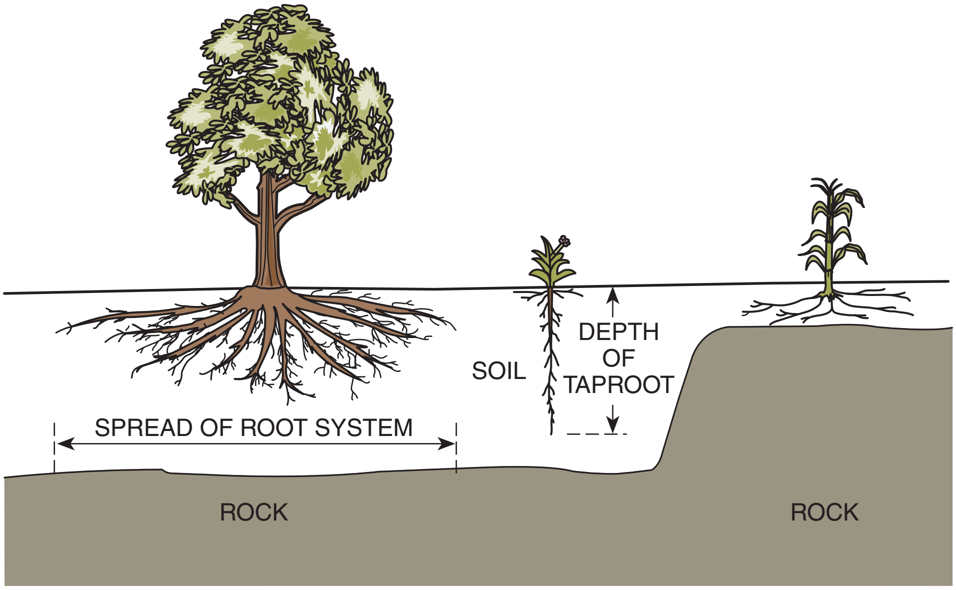
Soil Profile

The earth consists of a solid, molten core approximately 4000 miles (6400 kilometers) from the surface, a rocky mantle, and a crust that is 20–30 miles (32–48 kilometers) thick (Figure 12-4). Soil is defined as the biochemically weathered, uppermost portion of the earth's crust. Thus, the soil, though varying in actual depth around the earth, forms a very thin layer. Depending on a geographical area's soil-forming ability and the climate, the soil layer may range from only



Ron Nichols, USDA-NRCS.

FIGURE 12-1
Soils are the foundation for our modern agricultural systems. Aerial view of contour strip-cropping in central Wisconsin. This is a cropping approach to conserve the soil.



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FIGURE 12-2
Soils provide a medium for plant growth and a source of support for the upright growth of stems. Plant roots explore the soil and extract water and nutrients.





David L. Hansen, University of Minnesota.

FIGURE 12-3
We use soils for recreational (above) and building purposes (below).

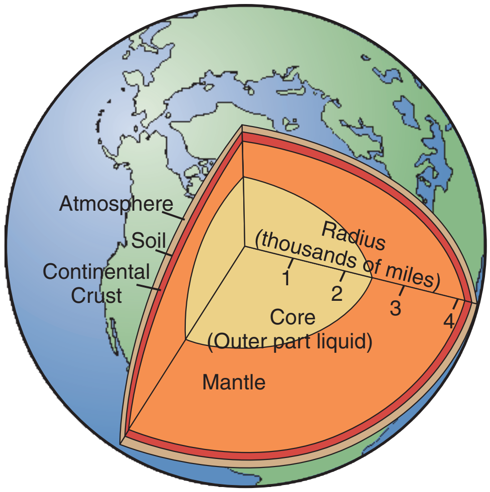


FIGURE 12-4
Cross section of the earth. The soil is a thin layer formed on the earth's surface. If the soil were drawn to scale, it would be 1/2,000,000 of an inch (0.0000127 millimeter) thick. 1000 miles = 1609 kilometers.

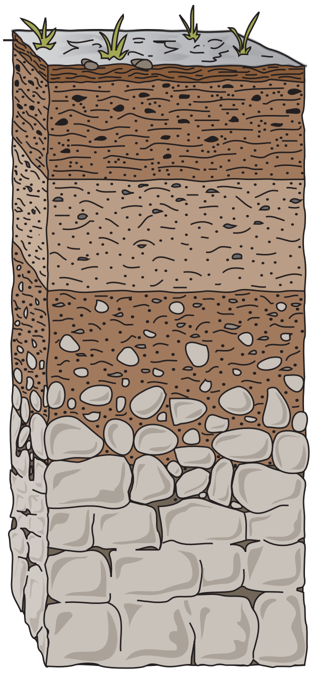


FIGURE 12-5
A soil profile showing the primary horizons. Most plant roots are found in the top 12 inches (31 centimeters) of soil. Soils are formed through the action of climate and organisms on the rocky, parent material.

inches in depth to many feet. In most agricultural regions, the soil layer is 3–4 feet (0.9–1.2 meters) thick.

An excavation of the soil in a field will show its **profile** (Figure 12-5). A profile is a vertical section through the soil extending from the surface to the unweathered rock of the crust layer. Each soil type has a unique profile with distinct layers or **horizons** that are formed during the weathering process. A profile's A horizon is highest in fertility and organic matter. It is also called the **topsoil**. The A horizon appears brown or black in color because of its high organic matter content. Plant roots and soil organisms are found mostly in the A horizon. The O layer is the organic matter layer of plant material in various states of decay on the surface of the mineral soil. The B horizon is often called *subsoil* and is a zone that accumulates compounds and minerals that water

has leached from the surface horizons. Finally, the C horizon is a zone with few plant roots and little weathering. It may be similar to the rocky, parent material beneath it.

Sometimes, agricultural operations can cause modification of the characteristics in the A or B horizons. Compaction due to wheel traffic and repeated plowing to the same depth can cause hard pans. These are cemented layers that impede vertical water flow and plant rooting.

Soil Orders

Soil scientists have systematically classified soils by using a system that parallels the plant taxonomy system described in Chapter 4. Soil order is the broadest classification. Twelve soil orders apply to soils in the United States (Table 12-1 and Figure 12-6). These soils vary in their potential productivity for agricultural use. Soil profiles can vary depending on the types of soils (Figure 12-7). For example, the soils formed under grasslands in the central United States have a deep, darkly colored A horizon that is very fertile and high in organic matter. These soils are called **Mollisols** and are important for agricultural production. In comparison, many soils formed in warm and wet tropical regions are often low in organic matter content and lack distinct horizons.

TABLE 12-1

Descriptions of soil orders. These are the 12 soil orders that occur in the United States. *Adapted from Plaster (2003), Powers and McSorley (2000), Chiras and Reganold (2005), and the NCRS (2007).*

Alfisols are formed under hardwood forests in temperate, moist climates. Alfisols are usually fertile and have good crop production potential, but they are sometimes acidic. They make up about 14.5 percent of the U.S. surface area and predominate in the Great Lake states and along the Mississippi River basin.

Andisols are formed from weathered volcanic materials. They can contain from 10–20 percent organic matter and have a high natural fertility. They can be used for cropland, pastures, and forests. They make up about 1.7 percent of the U.S. surface area and are found in the Pacific Northwest, Hawaii, and Alaska.

Aridisols are desert soils found mostly in the western and southwestern United States where precipitation is inadequate for crop growth. They are used for rangeland and for irrigated cropland. Because of the lack of rainfall, overgrazing of these soils causes considerable damage. They make up about 8.8 percent of the U.S. surface area.

Entisols are relatively undeveloped soils that lack defined horizons in their profiles. They are formed from volcanic deposits, floodplains, or eroded slopes. They are distributed throughout the United States. They vary greatly in crop production potential. Floodplains are typically highly productive. Entisols make up about 12.2 percent of the U.S. surface area.

(*Continued*)

TABLE 12-1 (Continued)

Gelisols are very cold soils with permanent frost within 40 feet (100 centimeters) of the soil surface. They are found in the tundra of Alaska. They make up about 7.5 percent of the U.S. surface area.

Histosols are organic soils often found in wetlands such as peats, bogs, and muck. They have greater than 20 percent organic matter. Histosols are found in northern Minnesota and Wisconsin as well as Florida and Louisiana. Peat soils contain partially decomposed organic matter and are harvested for horticultural use. Muck soils can be used for vegetable production if drained of excess water. Cranberries and wild rice are typically grown on flooded Histosols. They make up about 1.3 percent of the U.S. surface area.

Inceptisols are relatively young soils formed under the same circumstances as Entisols but with more horizon development. They are often found on sloping landscapes. They are present in the New England states and Appalachia as well as the Pacific Northwest. They are used for cropland and forestland. They make up about 9.1 percent of the U.S. surface area.

Mollisols are soils formed under grasslands in the northern and southern plains states. They have a dark, A horizon with high organic matter. They are very fertile and are the foundation for the corn and soybean cropping system in the Midwest. They make up about 22.4 percent of the U.S. surface area.

Oxisols are highly weathered, low-nutrient tropical soils found in Hawaii and Puerto Rico. They tend to be low in organic matter. They require careful management for crop production. They are used for forests and crops such as sugarcane. They make up less than 0.01 percent of the U.S. surface area.

Spodosols are found in coniferous forests in cold and humid regions. These soils are often sandy and low in fertility. Nutrients have been leached from A horizons to subsurface horizons. They are found in northern Minnesota, Wisconsin, and Michigan as well as the New England states. They are best suited for natural forest vegetation and for cropland, only if fertilized. They make up about 3.3 percent of the U.S. surface area.

Ultisols are highly weathered soils in humid, warm climates, often under forestation. They are often acidic and high in iron that, when oxidized, imparts a red color to the profile. A mixed coniferous and hardwood forest vegetation was the permanent vegetation on these soils at the time of European settlement. They predominate from Pennsylvania to the southeastern United States. They can be very productive for a diversity of crops but may be acidic. They make up about 9.6 percent of the U.S. surface area.

Vertisols are clayey soils that have deep, wide cracks during dry periods of the year. They shrink as they dry and swell as they become moist. The natural vegetation is predominantly grass, savanna, open forest, or desert shrub. They are found in Texas, Louisiana, and Arkansas and make up about 1.7 percent of the U.S. surface area.

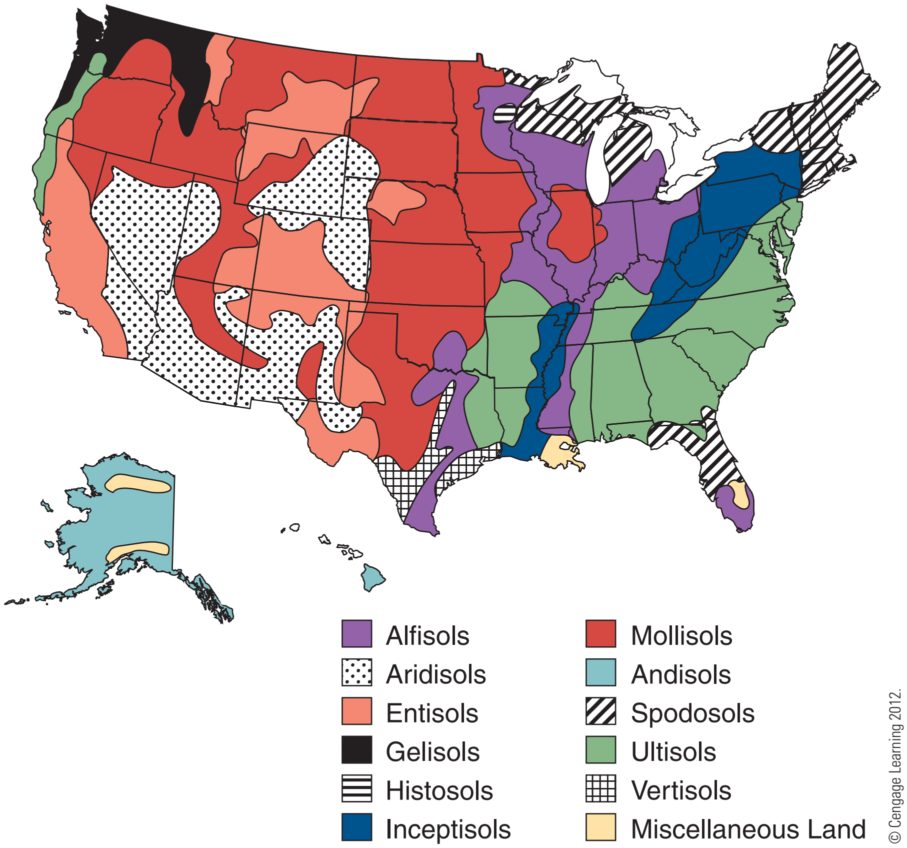


FIGURE 12-6
Major soil orders of the United States.

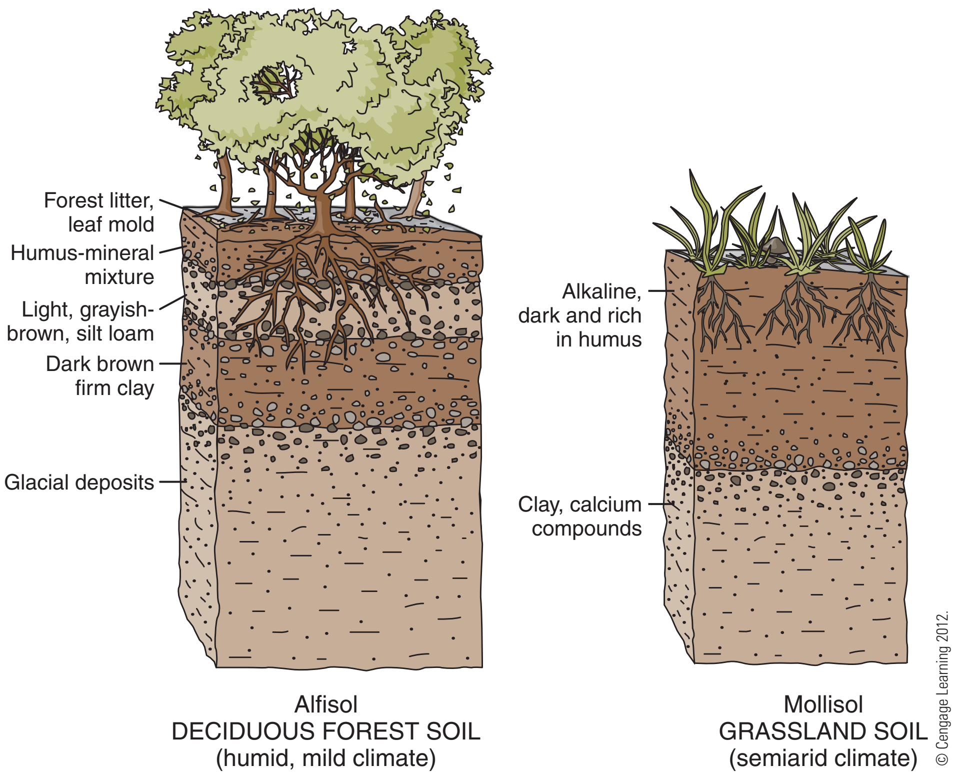


FIGURE 12-7
Soil profiles of Alfisols and Mollisols, two soil orders. Alfisols develop under deciduous forests in humid climates. Mollisols develop under grassland vegetation. These soils are well known for their dark brown to black, rich, organic surface layers.

A Look at Soils

Soils are a mixture of minerals, organic matter, liquids, and gases (Figure 12-8). Productive agricultural soils typically consist of about half solids and half pore space. The solids are minerals derived from rock and organic matter. Pore spaces are filled with air and water. Living organisms such as microbes, earthworms, and rodents are also important components of the soil.

Rocks and Minerals

The **parent material** for most soils is rock from the earth's crust. These rocks are weathered into minerals that become the major components of soils. These minerals are composed of elements that are required for plant growth. Consequently, the principal minerals found in our soils reflect the composition of the earth's crust (Table 12-2). Silicates (silica and oxygen compounds) and aluminosilicates

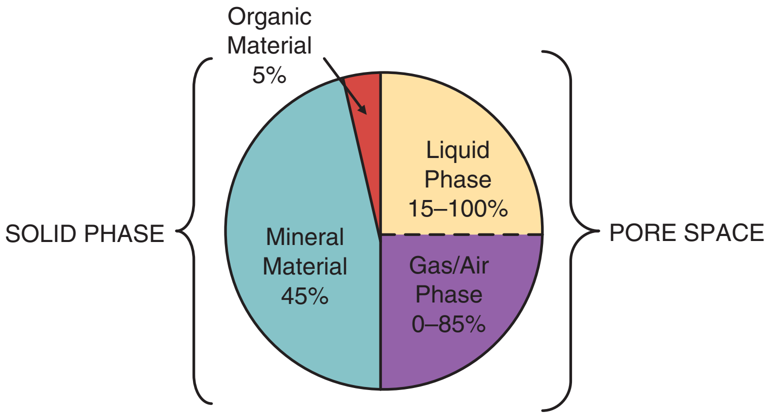


FIGURE 12-8 The average composition of a soil.

TABLE 12-2

The most common elements in the earth's crust. *Adapted from Coyne and Thompson (2006) and Gabler et al. (1991).*

Element	%, by weight	%, by volume
Oxygen (O)	46.6	93.8
Silicon (Si)	27.7	0.9
Aluminum (Al)	8.1	0.5
Iron (Fe)	5.0	0.4
Calcium (Ca)	3.6	1.0
Sodium (Na)	2.8	1.3
Potassium (K)	2.6	1.8
Magnesium (Mg)	2.1	0.3

(aluminum plus silica and oxygen compounds) predominate. The earth's crust has three primary types of rock—sedimentary, igneous, and metamorphic.

Sedimentary rock is the predominant parent material for soils on the earth. It is formed when wind and water deposit minerals. These sediments become solidified under pressure, and rock is formed. Sedimentary rocks tend to be in layers and may include fossils. Limestone, sandstone, and shale are types of sedimentary rocks.

Igneous rock is formed under extreme volcanic heat, followed by periods of cooling and hardening. Many of these rocks were formed in prehistoric times, but volcanic activity continues to produce them today. Granite and basalt are types of igneous rocks.



Soil Formation

Agriculturally productive soils are formed over many years by the interactions of climate, biological organisms, chemical forces, and physical forces on sedimentary, igneous, and metamorphic rocks (parent materials). The factors that influence soil formation include the following:

- Climate factors that are especially important in soil formation are precipitation and temperature. Water from rainfall erodes rocks and also can leach nutrients and minerals into the soil. It is also essential for plant and microorganism growth. Temperature influences the rate of plant growth, chemical reactions, and rock weathering.
- Physical factors that influence the production of soil include water movement, water freezing and thawing, glaciations, and wind. The expansion and contraction of water and minerals is especially important in the degradation of rocks. In North America, glaciation was a major factor affecting soil formation. Glaciers and their melt water rearranged landscapes by transporting and depositing rocks and soils. Today, water still significantly affects soil formation as it erodes, transports, and deposits soil sediment on floodplains and deltas.
- Biological factors needed for soil production include the action of plant roots on rock. Plants can break rocks apart as roots wedge into cracks. Also, the decay of plants produces organic matter that, during decomposition, produces acids that dissolve rocks. Organic matter from plants can also accumulate and create unique soils such as the Mollisol soils. Lichens and fungi growing on rock surfaces can dissolve the rock by the excretion of chemical compounds.
- Chemical reactions that are involved with soil production include oxidation, carbonation, and hydrolysis. An example of an hydrolysis reaction is the breakdown of limestone, a sedimentary rock, during reaction with water:

$$\text{Limestone } (CaCO_3) + H_2O \longrightarrow H_2CO_3 + Ca$$

Metamorphic rock is formed by the action of heat and pressure on other types of rocks. For example, under the correct conditions of heat and pressure, sedimentary rocks such as limestone may be converted to marble, and shale may be converted to slate.

Essential Elements

Essential elements are those that are necessary for a plant to complete its growth cycle, whose functions cannot be replaced by other elements, and that are components of a molecule or an enzyme within the plant. Minerals derived from rocks provide many of the essential nutrients for plant growth.

Seventeen elements are essential for plant growth (Tables 12-3 and 12-4). Of these elements, plants obtain carbon, oxygen, and hydrogen from the air. Plants

TABLE 12-3

Essential elements and their concentrations in plants. *Adapted from Barden et al. (1987) and Plaster (2003).*

Element	Concentration in tissue (dry weight)
Macronutrients	**%**
Carbon (C)	45.0
Hydrogen (H)	6.0
Oxygen (O)	45.0
Nitrogen (N)	1.5
Phosphorus (P)	0.2
Potassium (K)	1.0
Calcium (Ca)	0.5
Magnesium (Mg)	0.2
Sulfur (S)	0.1
Micronutrients	**Parts per million (ppm)**
Iron (Fe)	100
Manganese (Mn)	50
Copper (Cu)	6
Zinc (Zn)	20
Boron (B)	20
Molybdenum (Mo)	0.1
Chlorine (Cl)	100
Nickel (Ni)	0.5
Elements that are sometimes beneficial	
Sodium (Na)	
Silicon (Si)	
Cobalt (Co)	
Vanadium (V)	

TABLE 12-4

Specific metabolic functions and deficiency symptoms of essential elements in plants. *Adapted from Stern (1994).*

Element	Functions	Some deficiency symptoms
Nitrogen	Part of proteins, nucleic acids, coenzymes, chlorophyll	Loss of color in leaves, seen first on the oldest leaves
Phosphorous	Part of energy transfer system as ATP, nucleic acids, proteins, phospholipids	Stunted growth; leaves darker than normal; lower leaves purplish between veins
Potassium	Activates enzymes; important in stomata movements; concentrates in meristems	Yellowing of leaves, beginning at margins; lower leaves brown at tips
Calcium	Part of middle lamella; movement of substances through cell membrane; enzyme activator	Terminal bud often dead; tips and margins of leaves withered; roots dead or dying
Iron	Needed for light-driven reactions of photosynthesis; oxygen transport	Larger veins green while rest of leaf yellows, primarily in young leaves
Sulfur	Part of some amino acids and coenzymes	Leaves pale with dead spots; veins lighter in color
Magnesium	Part of the chlorophyll molecule; enzyme reactions involving ATP	Leaves are yellow with green veins and dead spots; leaf margins curling
Chlorine	Electron transfer from water to chlorophyll in photosynthesis	Yellowing of leaves, wilting
Boron	Translocation of sugar; synthesis of RNA and DNA	Petioles and stems brittle
Manganese	Activates some enzymes	Dead spots scattered over leaf surface with green veins on the youngest leaves

acquire the others from the soil. Based on their average concentrations in plant tissue, elements are classified as either macronutrients or micronutrients. Additional amounts of nitrogen, phosphorus, and potassium are often added to soils through fertilizers.

Organic Matter

Organic matter is the portion of the soil that includes animal and plant residues in various stages of decay. The organic matter content of a soil varies greatly depending on the climate. Grassland soils have some of the highest organic matter content (Table 12-5).

Complex carbon compounds make up organic matter. Soil microbes rapidly digest compounds such as starch, cellulose, sugars, and amino acids (Figure 12-9). Some soil fractions such as lignin and waxes are resistant to decay and ultimately form stable organic matter called *humus*. Over time, most of the carbon in organic

TABLE 12-5

Distribution of soil organic matter in various ecosystems. *Adapted from Schlesinger (1997) and Coyne and Thompson (2006).*

	Mean soil organic matter content		Total soil carbon (world)	
Ecosystem type	pounds/cubic yard	kilograms/cubic meter	tons × 10^9	tonnes × 10^9
Forests				
Tropical forests	17.5	10.4	281	255
Temperate forests	19.9	11.8	157	142
Boreal forests	25.1	14.9	197	179
Woodlands and shrublands	11.6	6.9	65	59
Grasslands				
Tropical savannas	6.2	3.7	62	56
Temperate grasslands	32.4	19.2	191	173
Cultivated	21.4	12.7	196	178
Tundra and alpine	36.4	21.6	191	173
Deserts				
Desert scrub	9.4	5.6	111	101
Extreme deserts, rocks, ice	0.2	0.1	3	3
Swamps and marshes	115.6	68.6	151	137

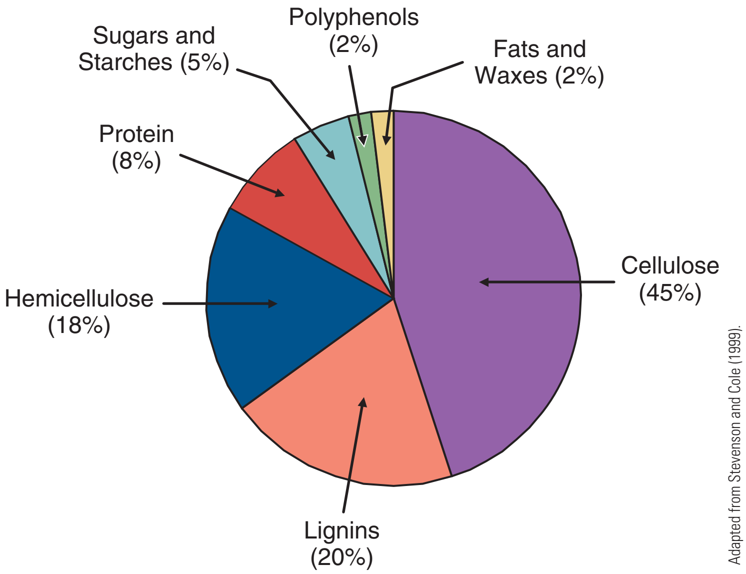


FIGURE 12-9 Typical composition of decomposed organic matter from plants.

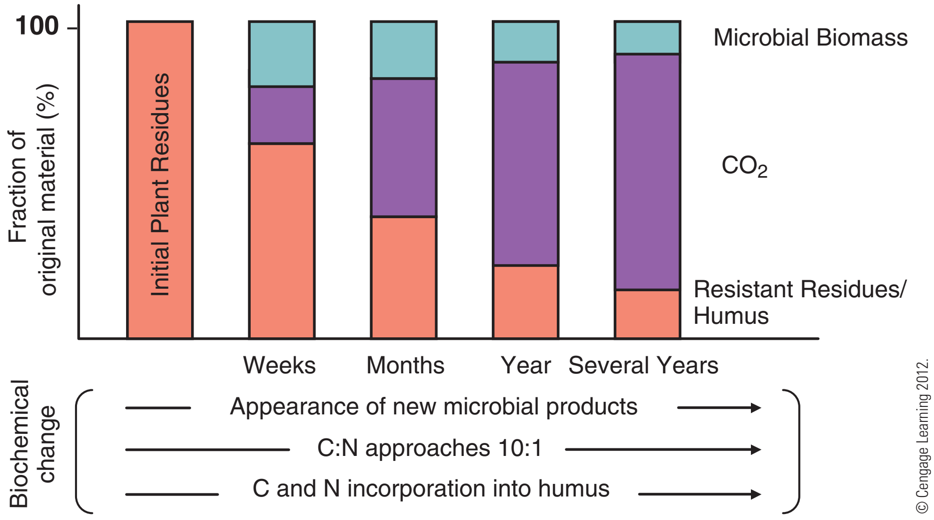


FIGURE 12-10 Physical and biochemical succession during plant organic matter (residue) decomposition in soil.

matter is converted to carbon dioxide (CO_2) with a small amount of resistant residue or humus remaining (Figure 12-10).

An important factor influencing the rate of decomposition of plant materials in the soil is the relative content of carbon and nitrogen in the material. This is expressed as the **carbon:nitrogen ratio (C:N ratio)**. C:N ratios vary among plant species or plant components (Table 12-6) and the rate of decay decreases as the C:N ratio increases. Plants with a low C:N ratio such as alfalfa are nitrogen-rich and decay rapidly, whereas sawdust with a high C:N ratio is nitrogen-poor and decays very slowly. This relationship occurs because bacteria and fungi that decompose plant and animal residues need nitrogen for growth. If inadequate nitrogen is available, the number of microorganisms will be insufficient to decay the plant material. When C:N ratios are more than 30:1, all of the available nitrogen in the soil is to sustain existing microbe populations. At higher C:N ratios, not enough nitrogen is available for decomposition and nitrogen can be temporarily immobilized. Therefore, if sawdust is added to a soil, the crops may be nitrogen-deficient, and extra nitrogen fertilizer may be required.

Organic Matter Functions

Particles of decomposed organic matter are very small, yet they have a relatively large surface area that is chemically reactive. Overall, organic matter has a negative charge. This large surface area attracts water and nutrients, and influences the organic matter's functions. The functions of organic matter include the following:

- **Sequestration of nutrients such as carbon.** Because carbon is a major component of organic matter, organic matter is therefore an important component of the global carbon cycle.
- **Source of nutrients.** Organic matter serves as a reservoir for essential nutrients such as nitrogen, phosphorus, and boron. These nutrients are either attached to the surface of the organic matter or are a component of the organic matter.

TABLE 12-6

The carbon-nitrogen (C:N) ratios of several materials. The lower the ratio, the richer its nitrogen content and the greater the rate of decay in the soil. *Adapted from Plaster (2003)*.

Material	C:N ratio
Soil humus	10:1
Garden soil	12–15:1
Young alfalfa	12:1
Compost	15–20:1
Rotted manure	20:1
Clover residue	23:1
Corn stover	60:1
Straw or leaves	60:1
Sawdust	400:1

- **Soil aggregation and structure.** Organic matter is a binding agent that joins the mineral portions of the soil together. Aggregation of soil particles is important in soil tilth and aeration.
- **Water storage.** Organic matter absorbs water like a sponge and retains it for plant growth.
- **Chemical sequestration.** Organic matter can tie up toxic chemicals and pesticides that would otherwise contaminate groundwater.

Soil Organisms

A healthy soil is alive with microorganisms and macroorganisms living together in a food web that involves energy and nutrient conversions. Fungi, bacteria, earthworms, insects, and more complex vertebrate organisms such as rodents and snakes live in the soil (Table 12-7, Figure 12-11). Photosynthesis by plants, bacteria, and algae is the energy source for soil food webs.

Earthworms

Often we think the primary role of earthworms is fishing bait, but they should also be associated with healthy agricultural soils. They are often the most frequently observed soil organism, and some moist, northern soils contain as many as 350 per square yard (300 per square meter). Earthworms play several critical roles in enhancing soil quality.

- They shred crop residues and initiate decomposition of the organic matter by bacteria and fungi that feed on organic matter. Their excreta are in turn consumed by other soil organisms.

TABLE 12-7

Size, mass, and numerical relationships among soil organisms. *Adapted from Coyne and Thompson (2006) and Coleman and Crossley (1996).*

Organisms	Approx. length: millimeters	Approx. length: inches	Approx. biomass dry weight: kilograms/hectare	Approx. biomass dry weight: pounds/acre	Individuals per: 1000 cubic cm	Individuals per: 1000 cubic inches
Earthworms	15–85	0.6–3.3	25–50	22–45	2	0.1
Potworms	1.0–60.0	0.04–2.4	1–8	0.9–7.1	50	3
Arthropods	1–30	0.04–1.2			100	6
Nematodes	0.2–2.0	0.01–0.1	1.5–4.0	1.3–3.6	30,000	1800
Mites	1	0.04	2–8	1.8–7.1	2000	125
Collembola	0.5	0.02	0.2–0.5	0.2–0.4	1000	60
Protozoa					1,000,000,000	60,000,000
Naked amoeba	0.03	0.001	47.5	42		
Flagellates	0.01	0.0004	2.5	2.2		
Ciliates	0.08	0.003	<0.5	<0.4		
Fungi			700–2700	625–2409	billions	billions
Bacteria			500–750	446–669	billions	billions

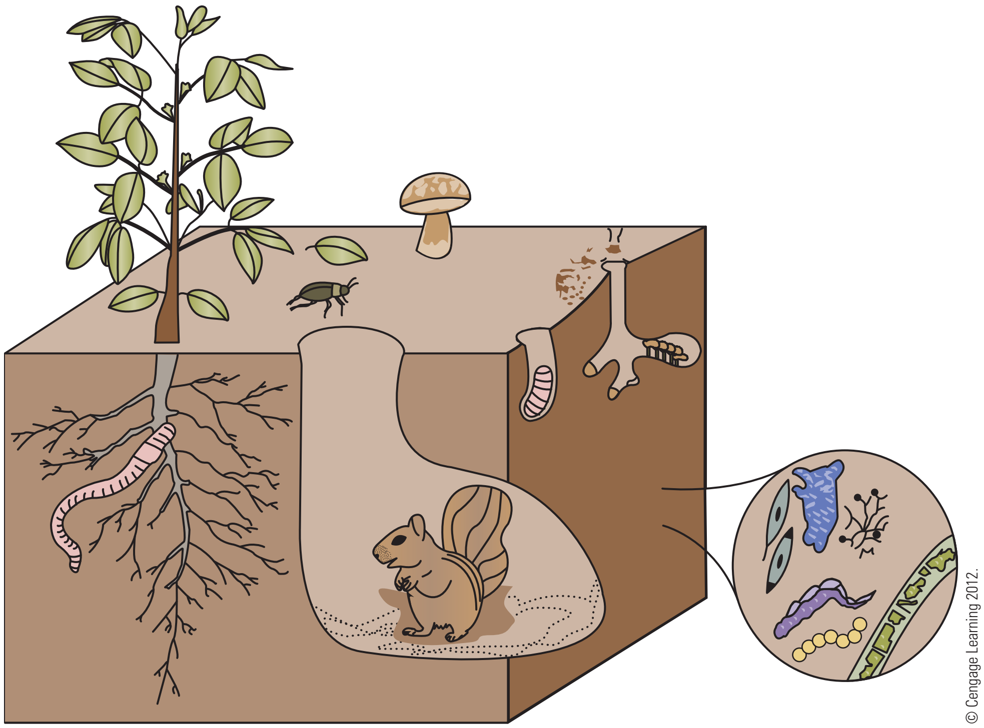


FIGURE 12-11
Soil micro- and macroorganisms inhabit the soil and are important in soil formation.

- They mix soil and organic matter. They bury organic matter within the soil, and they excrete a soil organic-matter aggregate "cast" on the soil surface.
- Earthworm tunnels aerate the soil and provide pathways for the movement of water and roots.

There are more than 7000 species of earthworms. Colonists introduced many species into North America. Earthworms are classified into three groups: litter-dwellers, shallow soil dwellers, and deep-burrowers. The deep-burrowing night crawler (*Lumbricus terrestris*) is the most well known of these worms. Night crawlers construct vertical burrows that can extend 5 feet (1.3 meters) into the soil. Earthworms are invertebrates (i.e., they have no spine). They have a segmented muscular body with a distinct head and tail. They burrow through cracks in the soil by using their heads as a wedge and specialized bristles on their forward segments to aid movement. Lubricating mucus on their skin reduces the friction as they move through the soil. They consume organic matter, digest it, and excrete an undigested residue-soil aggregate in a cast. We find dried casts on the soil surface, and they can be concentrated sources of plant nutrients.

Environmental conditions and crop management greatly influence earthworm populations. They prefer moist, yet well-drained soils. A surface residue food source is critical to support earthworm populations. Tillage that buries residue and disrupts burrows decreases earthworm populations. Surface residue also insulates the soil from extremes of temperature and reduces moisture loss. Therefore, no tillage is an improvement from conventional tillage (see Chapter 14) when it comes to promoting earthworms. The largest earthworm populations are typically achieved with perennial sod-forming crops. Pasture systems (with and without manure) that maintain a continuous sod surface residue and are not tilled increase earthworm populations (Table 12-8).

TABLE 12-8

Earthworm populations affected by crop and tillage systems. *Adapted from Kladivko (1993)*.

Crop	Management	Earthworms per square yard	Earthworms per square meter
Continuous corn	Plow	12	10
Continuous corn	No-till	24	20
Continuous soybeans	Plow	72	60
Continuous soybeans	No-till	167	140
Dairy pasture	Manure	407	340
Dairy pasture	Manure (heavy)	1555	1300

Fungi and Bacteria

Fungi often make up the largest microbial biomass in the soil. Fungi are very effective decomposers of plant material. However, some soil fungi may be pathogenic or harmful to certain plants. Other soil fungi may form a mutually beneficial relationship (symbiosis) with the plant by developing mycorrhizae that enable infected plant roots to absorb water and nutrients, especially phosphorus, better than noninfected roots.

Bacteria are the most abundant soil inhabitants. Some bacteria are active in the decomposition of organic matter. Other bacteria may form symbiotic relationships with plants such as the interaction between legumes and the bacterium *Rhizobium* that enables nitrogen fixation to occur.

Other Organisms

Arthropods, such as insects, millipedes, and centipedes, are also active in the breakdown of organic matter.

Soil Pore Space and Soil Water

Productive soils are not densely packed, but contain **pore space** occupied by air and water. Soils compacted by excessive traffic and tillage do not allow for penetration of roots or movement of water. Pore space is much greater in sandy soils than in clay soils. Gases from the air diffuse into the soil, creating an aerobic environment unless the soils are compacted or filled with water.

Soil water will fill small spaces around the soil particles. Different types of water are held in varying extents in soil (Figure 12-12). Within 48 hours after rainfall or irrigation, **gravitational water** drains through the soil. The soil water content after gravitational water drains is called **field capacity**. At field capacity, water is held in pore spaces but is readily available to plants. Plants extract this water until the soil water reaches a level called the **permanent wilting point**. At the permanent wilting point, the remaining water is tightly held on soil particles and is not available to plants.

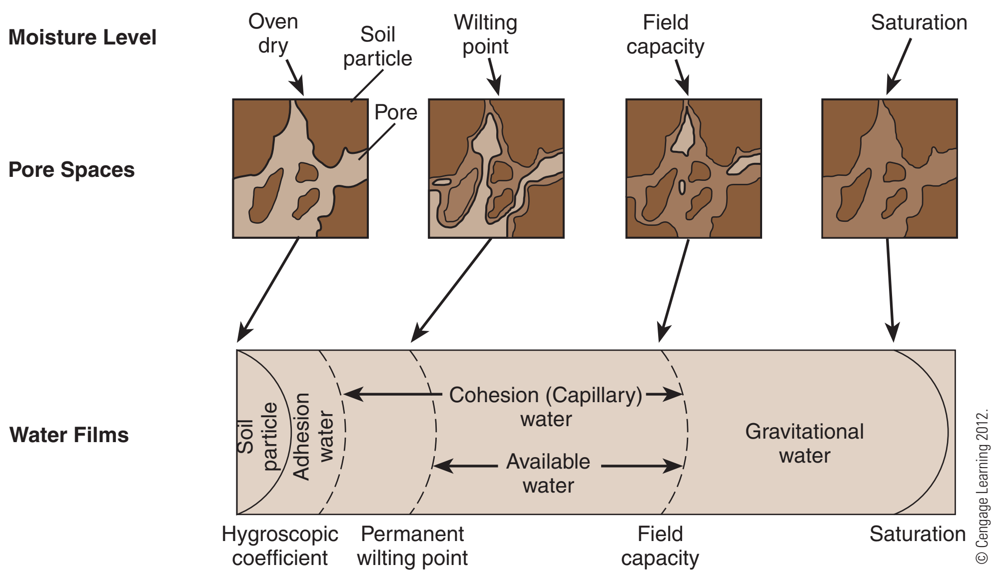


FIGURE 12-12 Water and air occupy soil pore space. Following rainfall and irrigation, all pores are filled (saturation). Gravity removes gravitational water until field capacity. Plants can use water until the permanent wilting point is reached.

Soil Properties

Based on the relative proportion of minerals, organic matter, and pore space, soils have textural, structural, and chemical properties that affect their potential uses.

Soil Texture

Soil texture describes a soil's fineness or coarseness. The soil texture, whether fine, coarse, or somewhere in between, is determined by the type and amount of specific soil particles—sand, silt, and clay. These particles are categorized by their sizes (Figure 12-13).

The weathering of rocks forms sand and silt. Chemically, sand and silt are mostly silica (SiO_2). They are discrete particles that do not attach to other particles. Sand is the largest soil particle and is composed mainly of weathered quartz, a primary component of sandstone, a sedimentary rock. Sandy soils have large pore spaces between particles and have relatively low internal surface areas. Sand and silt are relatively chemically inert and contribute few nutrients to plants.

Clay is the smallest soil particle. Clay particles are crystalline and layered, and they are composed of silica, aluminum, oxygen, hydrogen, potassium, magnesium, and phosphorus. Clay is chemically the most reactive particle and provides the most nutrients for plant growth. Clay particles attach easily to one another and when wet, clay soils become very sticky.

Most agricultural soils are a combination of the three soil particles, and soil scientists typically use a textural triangle to describe soils (Figure 12-14). The proportions of the three particles are determined mechanically. A loam soil has about 40 percent sand, 20 percent clay, and 40 percent silt. Soil texture has a great effect on soils' physical, chemical, and biological properties (Table 12-9). Water-holding capacity is an important soil property influenced by texture. Sandy soils have a large pore space between particles and hold less water than clay soils. Clay soils have the greatest water content at field capacity. Loam soils are intermediate in texture (Table 12-10).

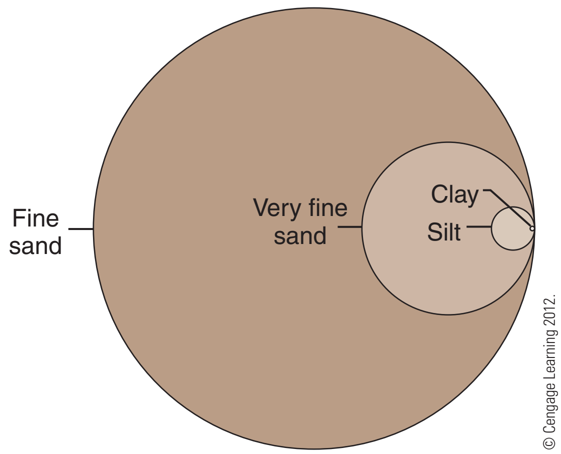


FIGURE 12-13
The relative size of sand, silt, and clay.

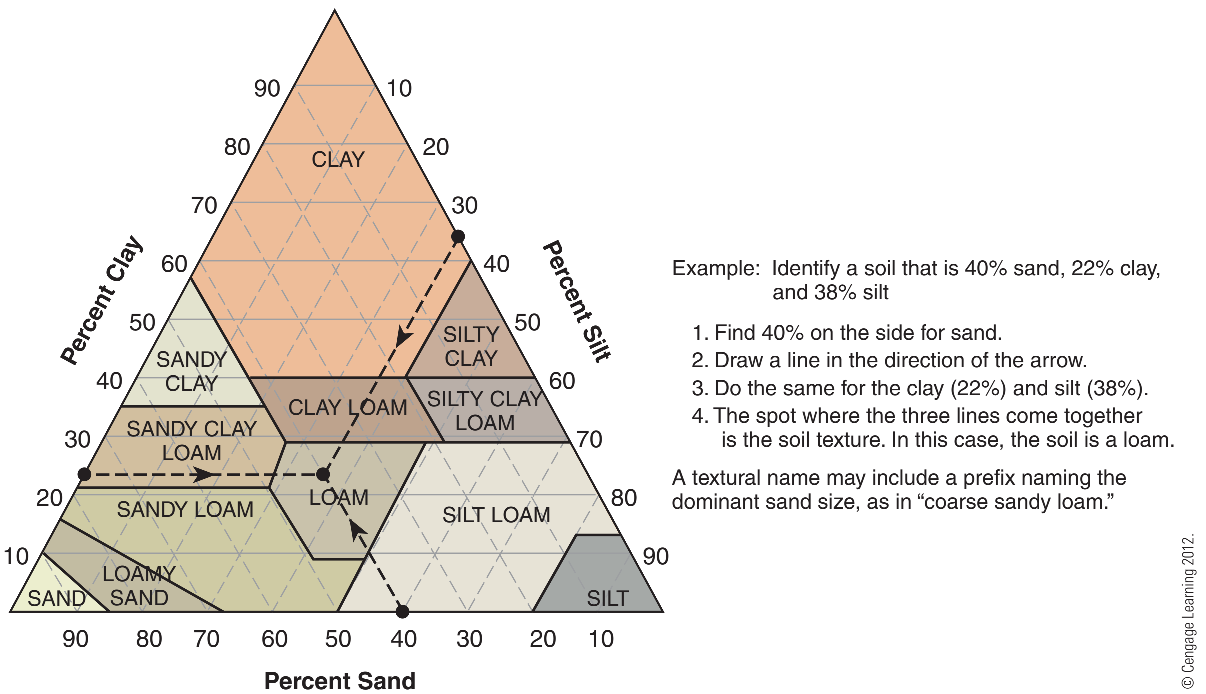


FIGURE 12-14 The soil textural triangle is used to characterize soil texture.

Soil Structure and Aggregation

Soil structure refers to the clustering of soil particles into various shapes. Productive agricultural soils often have a granular structure in which clusters of soil particles are bound together by organic matter and clay. Well-aggregated granular soils have good aeration and tilth. **Tilth** refers to soil having beneficial qualities related to crop growth. Soils that are primarily clay, or that have been damaged by excessive compaction, do not have good soil structure, are impermeable to water, are hard to till, and would not be considered to have good tilth.

Soil Chemistry

Soil has many chemical properties that affect plant growth, including cation exchange capacity, pH, and salinity.

Cation Exchange Capacity

Small, crystalline clay particles and organic matter in soil are chemically active with a negative surface charge. The negative surface charge of these particles enables them to attract positively charged ions (cations), water, and other chemical compounds such as pesticides (Figure 12-15). The amount of exchangeable cations a soil can sustain is called the **cation exchange capacity**. Soils that have a high cation exchange capacity hold nutrients and are fertile. The relative cation exchange capacities of clay, sand, and humus soils are about 30, 9, and 200 milliequivalents per 100 grams of soil each. Some of the exchangeable cations found in soils and their strength of attachment to soil particles include aluminum (Al^{3+}), with the

TABLE 12-9

Generalized influence of soil particles on some properties and behaviors of soils.

	Rating associated with soil separate		
Property/Behavior	**Sand**	**Silt**	**Clay**
Porosity	Low	Moderate	High
Percentage large pores	High	Moderate	Low
Total water holding capacity	Low	Moderate to high	High
Available water holding capacity	Low	Moderate to high	Moderate
Infiltration rate	High	Moderate	Low (unless cracked)
Drainage (percolation) rate	High to very high	Slow to moderate	Very slow
Aeration	Good	Moderate	Poor
Cation exchange capacity	Low	Low to moderate	High
Ability to store plant nutrients	Very low	Low to moderate	High
Resistance to pH change	Very low	Low to moderate	High
Soil organic matter level	Low	Moderate to high	High to moderate
Decomposition of organic matter	Rapid	Moderate	Slow
Shrink-swell potential	Very low	Low	Moderate to very high
Compactability	Low	Moderate	High
Root penetration	Easy	Moderate	Moderate to difficult
Ease of cultivation	Easy	Moderate	Difficult
Suitability for tillage after rain	Good	Moderate	Poor
Warm-up in spring	Rapid	Moderate	Slow
Detachability of particles	Easy	Moderate	Very difficult
Transportability of particles	Very difficult	Moderate	Easy
Susceptibility to wind erosion	Moderate	High	Low
Susceptibility to water erosion	Low	High	Low if aggregated, high if not
Sealing of ponds, dams, and landfills	Poor	Poor	Good
Pollutant leaching potential	High	Moderate	Low (unless cracked)

strongest attachment, followed in order by hydrogen (H^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), ammonia (NH_4^+), and sodium (Na^+). Knowledge of cation exchange capacity is important because it allows for an understanding of any necessary supplemental soil fertility requirements.

Soil Reaction (pH)

Soil reaction describes the concentration of hydrogen ions (H^+) in a soil. Soil reaction is also described as pH. The pH scale runs from 0 to 14 (Figure 12-16). A pH of 7 is neutral; a pH of 0 up to less than 7 is acidic; and a pH of greater than 7 up

TABLE 12-10

Soil texture influences how much water is held at field capacity and at the permanent wilting point, thus influencing the water available for plant growth. Available water is the water available for plant use. It is the amount of field capacity water minus the water at the permanent wilting point. 1 inch = 2.5 cm and 1 foot = 30.5 cm. *Adapted from Plaster (2003).*

Texture	Field capacity (inch/feet)	Permanent wilting point (inch/feet)	Available water (inch/feet)
Fine sand	1.4	0.4	1.0
Loam	3.1	1.1	2.0
Clay	3.9	2.5	1.4

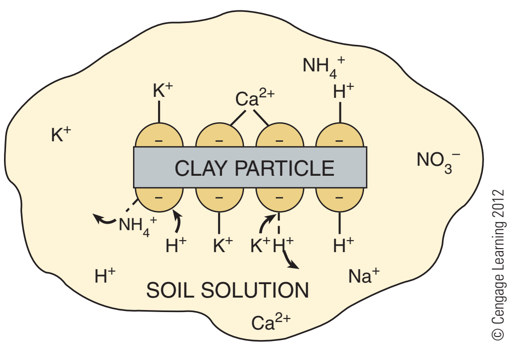


FIGURE 12-15 Clay particles and organic matter in soil are negatively charged, so their surfaces adsorb positively charged ions (cations) such as K^+, Ca^{2+}, and H^+. The negatively charged nitrate ion (NO_3) is not adsorbed and is leached from the soil by water.

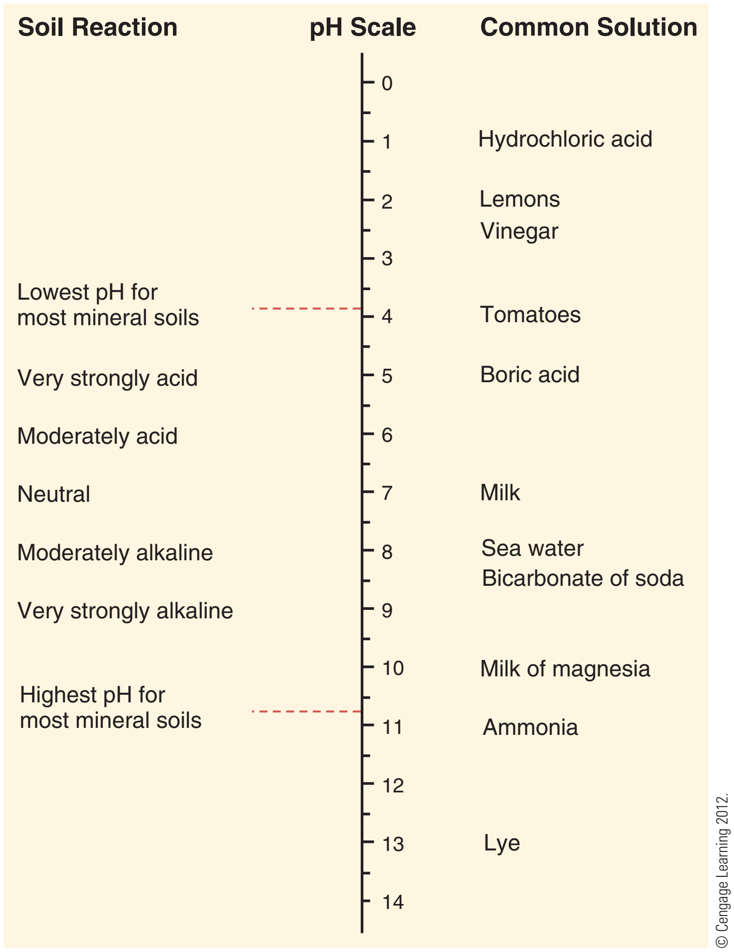


FIGURE 12-16 The pH scale showing relative acidity or alkalinity of various solutions.

to 14 is alkaline or basic. Plants vary in the required soil pH range for optimum growth (Figure 12-17). Soil pH is critical for the following reasons:

- Plants vary in the required pH range for best growth and yields (Figure 12-17). Most important field crops grow best at a pH of 6–7. However, some crops such as potato and blueberry grow best at a pH or 5 or less.
- pH influences the nutrients available to plants (Figure 12-18). A soil pH of 5 may limit phosphorus availability to plants even though soil phosphorus levels are adequate.
- Low soil pH may cause toxic levels of available aluminum and manganese in the soil. Aluminum toxicity inhibits root growth and restricts calcium uptake.
- pH affects the growth of beneficial soil organisms that form symbiotic relationships with legumes and facilitate biological nitrogen fixation.

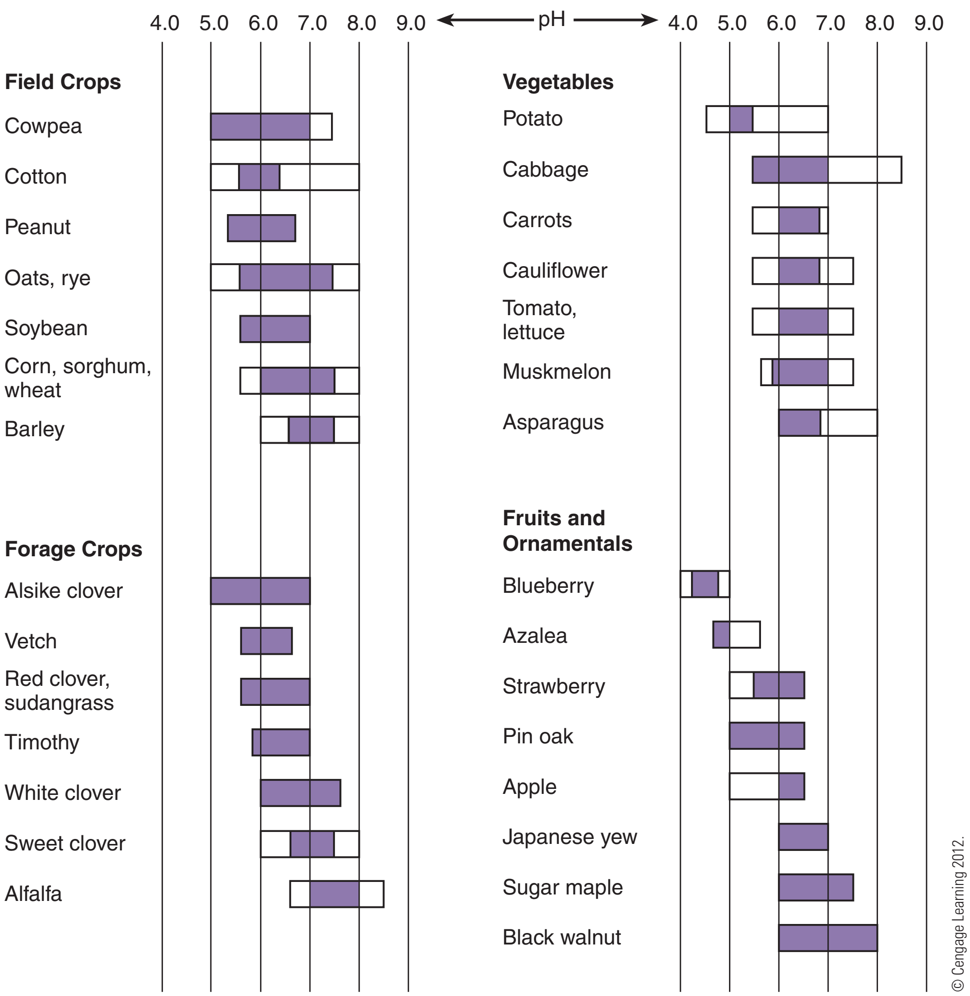


FIGURE 12-17
The horizontal bars represent the pH range of several crops. The optimum pH is shaded.

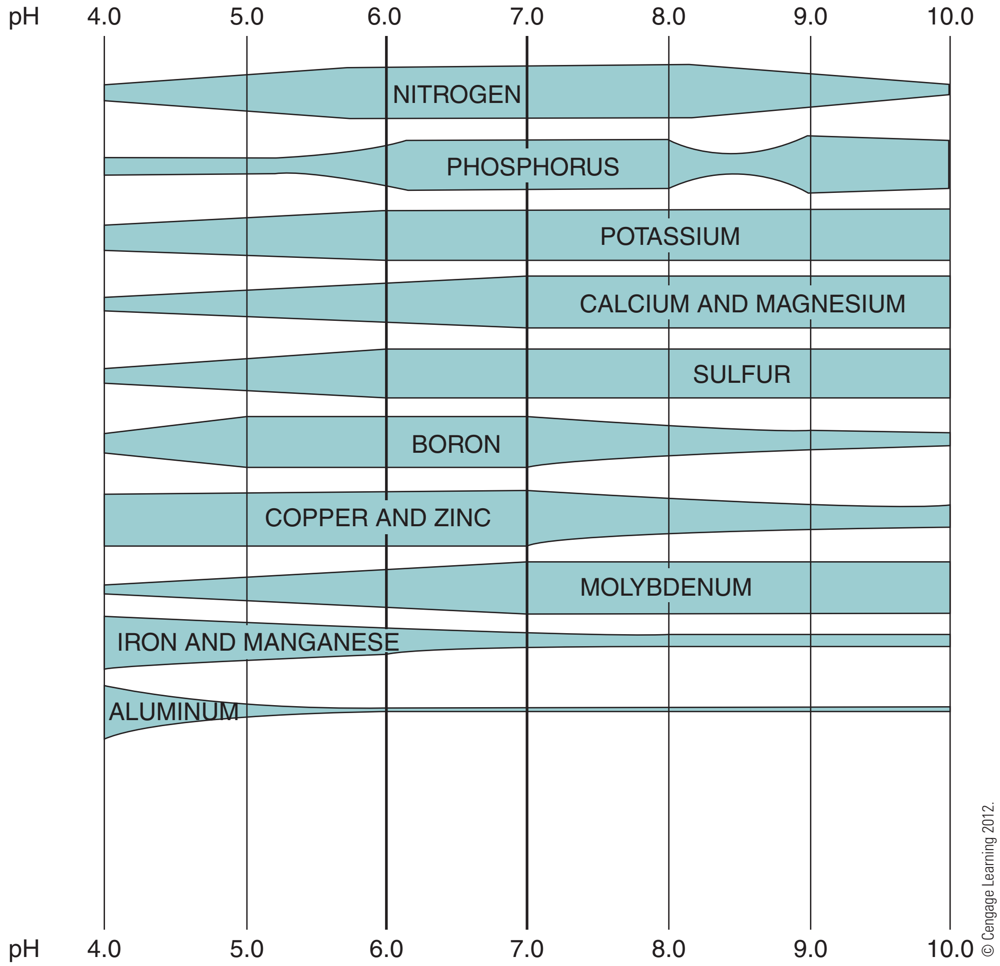


FIGURE 12-18
Soil pH affects plant growth by influencing the availability of soil minerals. The width of the bar on the diagram indicates the availability of the mineral to the plant. High levels of aluminum in the soil at low pH can be toxic to plants.

Salinity

Saline, *sodic*, and *saline-sodic* are terms used to describe soil **salinity**. Salinity occurs due to the accumulation of soluble salts (sodium, calcium, magnesium, and potassium) that dissolve in water. Salts form as a result of a chemical reaction between an acid and a base. Most soil salts are sulfates (SO_4), chlorides (Cl^-), carbonates (CO_3^{2-}), or bicarbonates (HCO_3^-). Saline soils typically occur in dry regions where salts rise to the soil surface during water evaporation and then accumulate there. A high concentration of salt in soils can cause a breakdown in soil structure. Soil is frequently saline in irrigated, dry land regions where the evaporation rate exceeds the rate of leaching of salts down into the soil by rainfall. Salts cause plant dehydration. Crops vary in their tolerance of soil salinity, but most crops are intolerant of high levels (Table 12-11). Other types of soil salinity are associated with accumulation of sodium (sodic soils) or of both saline and sodium (saline-sodic soils).

TABLE 12-11

Tolerances of selected crops to soil salinity.

Type of crop	Tolerant	Medium	Sensitive
Field crops	Barley	Corn	Beans
	Sugar beet	Soybean	Flax
	Cotton	Sorghum	Broad bean
		Wheat	
Forage crops	Bermuda grass	Alfalfa	Clovers
	Wheat grass	Orchard grass	
	Tall fescue	Perennial rye	
Vegetables	Beets	Spinach	Lettuce
	Asparagus	Tomato	Bell pepper
		Broccoli	Onion
		Cabbage	Carrot
		Potato	Beans
		Sweet corn	Celery
Fruits	Date palm	Grape	All others
		Fig	
		Olive	

Meeting the Nutritional Needs of Plants

Some soils are naturally fertile because they were derived from minerals rich in elements. Other soils, such as those formed over thousands of years beneath the tallgrass prairies of the Midwest, have high levels of available nutrients from organic matter. However, over time, most soils require fertilization for maximizing crop yields. Soil scientists have established relationships between fertility levels in the soil, plant tissue, and plant yield. The relationship between soil nutrient levels and yield is shown in Figure 12-19. Phase I shows nutrients are limiting plant

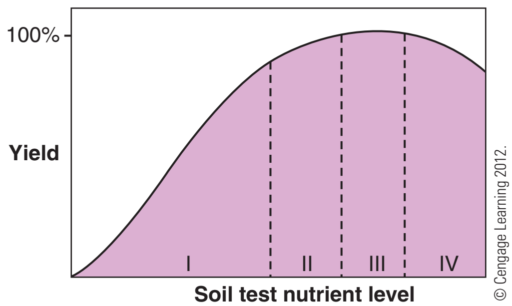


FIGURE 12-19
Crop grain or forage response to increasing levels of soil nutrients. Fertilization is usually most profitable in Level I. In Level II, the response to fertilization diminishes, and the process is less profitable.

growth, and there is a linear yield response to fertilization. Phases II and III show nutrient needs of the crop are met and no additional yield response occurs with additional fertilization. In the final phase, IV, the nutrients are at excessive levels, therefore becoming toxic or producing undesirable growth.

Determining Nutritional Needs

Producers use several methods to determine plants' nutritional needs. Soil testing laboratories have established soil sampling procedures. To test a soil, uniform depth samples are collected from multiple sites in an area by using a soil-sampling tube, auger, or spade (Figure 12-20). The soil samples are then submitted to a soil testing laboratory for chemical analysis. The report on the sample provides results, interpretation of the results, and recommendations (Figure 12-21). Recommendations for fertilizer application to crops are based on experimental trials within each state. Agricultural universities and commercial laboratories conduct research on different soils to determine the economically optimum fertilizer rate for crops.



Crop Productivity Index

The **Crop Productivity Index (CPI)** is a 0- to 100-value scale to rate soils for intensive agricultural production. The parameters of the index largely deal with the suitability of the landscape, soil, and regional climate for producing nonirrigated commodity crops. The index was developed by the National Soil Survey Center in Nebraska and utilizes soil survey information to be diagnostic in its rating system. The rating can be used to compare the potential yield rating of different soils in a given county, state, or region.

The model has corn and soybeans, small grains, and cotton sections. The model is then subdivided into important classifications that influence soil productivity including soil chemical properties, soil water components, soil physical properties, soil climate, soil landscape, and a scale of more subjective attributes that can harm or aid in soil productivity. Each of these categories has numerous subcategories that are utilized in the calculation of the total CPI of the soil.

The CPI is being used to replace the Crop Equivalency Rating (CER), which is another 0- to 100-value scale-rating system of soils that was created by University of Minnesota soil scientists. The CER was related to monetary productivity of agricultural land after the costs of inputs were factored in, rather than raw productivity of the soil. Many states had their own separate soil-rating systems that are being phased out in favor of a more universal CPI. See the Natural Resource Conservation Service website <http://www.nrcs.usda.gov/> for more information on the CPI system.

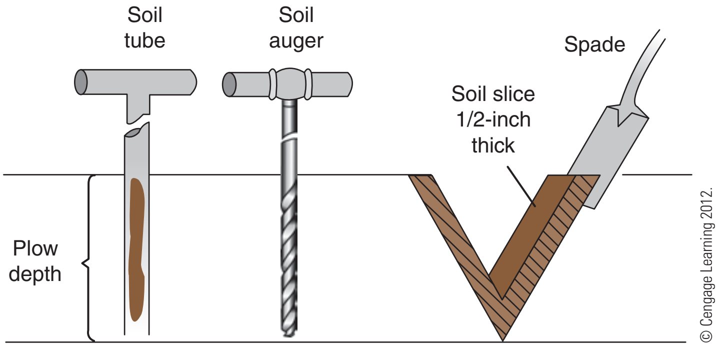
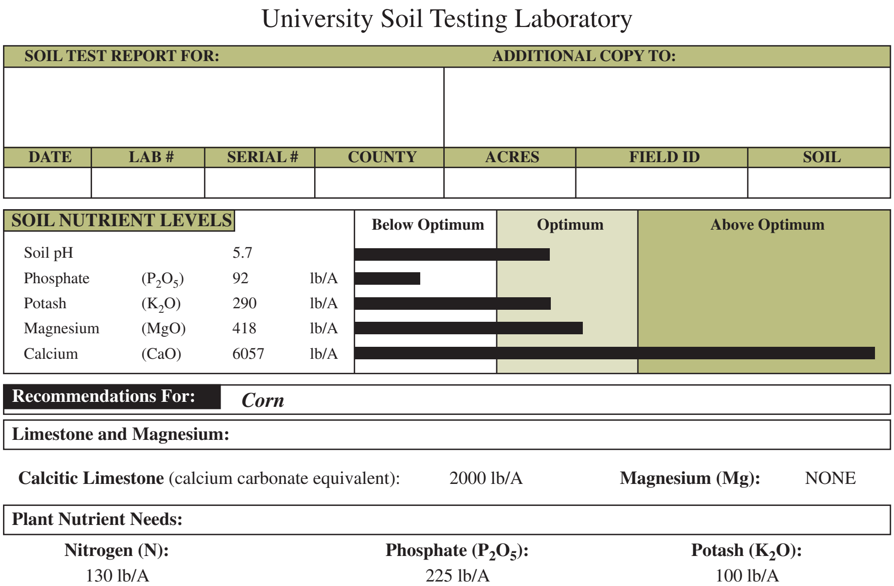


FIGURE 12-20
Soil samples can be taken using a soil tube, soil auger, or common spade.



University Soil Testing Laboratory

SOIL TEST REPORT FOR:				ADDITIONAL COPY TO:		
DATE	LAB #	SERIAL #	COUNTY	ACRES	FIELD ID	SOIL

SOIL NUTRIENT LEVELS				Below Optimum	Optimum	Above Optimum
Soil pH		5.7				
Phosphate	(P_2O_5)	92	lb/A			
Potash	(K_2O)	290	lb/A			
Magnesium	(MgO)	418	lb/A			
Calcium	(CaO)	6057	lb/A			

Recommendations For: *Corn*

Limestone and Magnesium:

Calcitic Limestone (calcium carbonate equivalent): 2000 lb/A **Magnesium (Mg):** NONE

Plant Nutrient Needs:

Nitrogen (N):	**Phosphate (P_2O_5):**	**Potash (K_2O):**
130 lb/A	225 lb/A	100 lb/A

FIGURE 12-21
A report from a soil testing laboratory. The report provides results of the soil test as well as recommendations for crops.

Tissue testing enables growers to analyze plant tissue to identify its levels of essential elements. This is particularly effective for identifying low concentrations of micronutrients. Tissue testing is widely used for high-value crops grown in nurseries, vineyards, or orchards and to a lesser extent with agronomic crops.

Fertilizers

The practice of supplementing plant nutrients by fertilization for the improvement of plant growth has been directly or indirectly employed since the dawn of agriculture. Early civilizations that were based on agriculture, such as those in Mesopotamia between the Tigris and Euphrates Rivers, often relied on annual flooding of the rivers to renew the nutrients in the soil. Later, the Greeks and Romans promoted the use of livestock manure, green manures, and crop rotation. During the nineteenth century, scientists such as Justus von Liebig in Germany and John Lawes and John Gilbert in England established the idea of essential plant nutrients and proposed the use of chemical fertilizers.

Fertilizer is a material applied to the soil to supply mineral nutrients that promote plant growth. Fertilizers can contain a specific plant nutrient or several nutrients. Lime is a special type of fertilizer that can apply Ca or Mg, but most often is applied to lower soil acidity that can affect the availability of other nutrients. There are two basic classes of fertilizers: organic and inorganic.

Organic Fertilizers

Organic fertilizers are derived from living matter and contain the element carbon (C). Animal manures, composts, and green manures are examples of commonly used organic fertilizers. Organic matter from animal manures and plants must first decompose to release their nutrients into the soil. This decomposing process takes time depending on the C:N ratio of the animal or plant manure. Usually, the nutrients in animal and plant manures are not completely available. Phosphorus (P) and potassium (K) may be available from 80 percent to 90 percent; nitrogen (N) availability averages only about 50 percent.

Animal manure is a combination of feces and urine produced by livestock, sometimes including livestock bedding material. It is a by-product of our meat, dairy, and poultry industries. The nutrients in animal manures reflect the plant nutrients originally fed to animals (Table 12-12). Animal manures are used extensively in crop-growing areas because they can be used as fertilizers to meet the nutritional needs of most crops. Grazing animals deposit manures directly on pastures, and the nutrients are recycled. Manures of confined animals must be transported to cropland.

Manure is a valuable resource as a soil amendment, but livestock produce a large quantity of manure that must be handled properly for efficient use of the nutrients. A 1000-pound (454-kilogram) dairy cow produces about 16 tons (14.5 tonnes) of manure every year. In confined animal facilities with 500 to 1000 dairy cows, a significant volume of manure is generated. Air and water quality can be affected negatively by these large volumes of animal manures. Therefore, manure nutrients must be carefully managed to take advantage of their fertilizer potential and to prevent loss of manure nutrients into the environment.

With seasonal crop production, animal manures must often be stored in specialized structures. Manure storage is associated with the generation of undesirable gases that are odoriferous and can cause health problems. Another issue with manure fertilizers is that care must be taken not to exceed the beneficial levels of certain nutrients that may already exist in the soil. For example, often there is an imbalance of nitrogen, phosphorus, and potassium levels in manure, and if manure is applied to corn to meet its nitrogen needs, many soils will have too much phosphorus.

Green manures are plants that are grown and plowed under when they are in a succulent condition with the goal of soil improvement and the addition of organic matter and essential elements. Numerous crops can be used as green manures, but legume crops are of particular value because they fix atmospheric nitrogen and provide this nitrogen to subsequent rotational crops. When used in rotation, one alfalfa crop can provide for all the nitrogen needs of a subsequent corn crop. Other crops such as rye (grown as a winter annual) and buckwheat cannot fix atmospheric nitrogen, but they do recycle and conserve nutrients and thereby enhance nutrient availability in the soil.

TABLE 12-12

Nutrient content of common manures. 1 pound/ton = 0.5 kilogram/tonne; 1 pound/1000 gallons = 0.12 kilogram/1000 liters. *Adapted from Coyne and Thompson (2006).*

	N	P_2O_5	K_2O	% moisture
Solid manures (lbs/ton)				
Beef	11	7	10	80
Dairy	11	9	12	80
Swine	9	9	8	82
Broiler				
Fresh	55	55	45	20
Stacked	60	70	40	30
Cake	60	70	40	30
Pullet	40	68	40	25
Breeder	35	55	30	40
Layer	30	40	30	40
Liquid manures (lbs/1000 gallon)				
Holding pit				
Swine	36	27	22	96
Dairy	31	15	19	94
Lagoon				
Swine	4	2	4	99
Dairy	4	2	3	98

Inorganic Fertilizers

Inorganic fertilizers are synthetic or mined and processed fertilizers that producers can apply to soil. Compared to organic fertilizers, the nutrients in inorganic fertilizers are more concentrated. Macro- and micronutrient fertilizers are available. Inorganic fertilizers are used to supply additional amounts of phosphorus, potassium, nitrogen, and calcium.

Phosphorus fertilizers are obtained from the mining of phosphate rock deposits. The rock can be pulverized and moved directly into the soil. Alternatively, the rock can be processed by treating it with acid and ammonia to increase phosphorus availability. Common dry phosphorus fertilizers are triple super phosphate (contains 20% P) and ammonium phosphate (contains about 23% P and 20% N).

Potassium fertilizers are also obtained from the mining and purifying of potassium deposits. Muriate of potash (potassium chloride) contains 60 percent K and is a common dry fertilizer.

Commercial nitrogen fertilizers are made through the Haber-Bosch process, which was invented in the early twentieth century. The process uses heat and

pressure in the presence of a catalyst to combine nitrogen from the air with hydrogen from natural gas. The product formed, ammonia (NH_3) gas, can be liquefied under pressure and used directly, or reacted with various compounds to form a diversity of products (Figure 12-22). Anhydrous ammonia, containing 82 percent nitrogen, is a cheap and widely used nitrogen fertilizer. It is carried to the field under pressure and injected into the soil (Figure 12-23). Urea and ammonium nitrate are nitrogen fertilizers applied in a granular dry form.

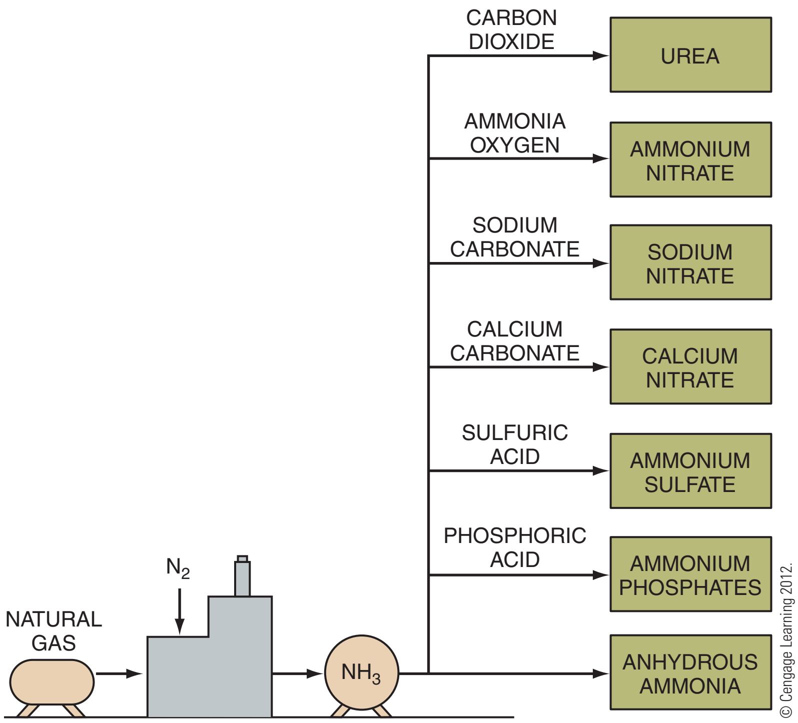


FIGURE 12-22 Nitrogen-containing fertilizers made through the reaction of atmospheric N and natural gas.



FIGURE 12-23 Injection of anhydrous ammonia into the soil. Anhydrous ammonia is a liquid under pressure in the tank and volatilizes after injecting. Anhydrous is a common source of N for fertilizing corn.

Limestone is a sedimentary rock available in many regions. It is used primarily to increase pH and secondarily to add calcium. It is mined and pulverized to achieve a regulated level of coarseness. Limestone is basic in pH and is applied to increase the soil pH which influences soil fertility.

Gypsum, calcium sulfate, is a naturally occurring mineral. It is a white powder used as a component of dry wall or sheet rock for construction. When applied to soil, it dissolves slowly and separates into the Ca^{2+} and SO_4^- ions. Gypsum is a source of calcium and sulfur for plant growth. Gypsum can improve the structure of saline or saline/alkali soils in the western United States by removing sodium from the profile. Although it contains both Ca and S, gypsum is a neutral salt; when it is applied to the soil, there is no change in soil pH.

Fertilizer Analysis and Grade

To protect consumers, the nutrient contents of commercially sold fertilizer must be listed on the packaging. This is called the fertilizer analysis or grade. The percentage of nitrogen (N), phosphoric acid (P_2O_5), and potash (K_2O) must be shown (Figure 12-24). Analysis of the fertilizer is simplified and expressed as N, P, and K. In addition, any other secondary nutrients in the fertilizers must be identified.

Applying Fertilizer

Fertilizers are applied at different times and in different manners depending on the crop (Figure 12-25). Specific terms used in describing fertilizer application include the following:

- **Broadcast application, also called *topdressing*.** Fertilizers, manures, and lime are often applied by broadcasting before the seeding of crops. In addition, established fields of perennial grass pastures and urban lawns are often fertilized using the broadcast method.

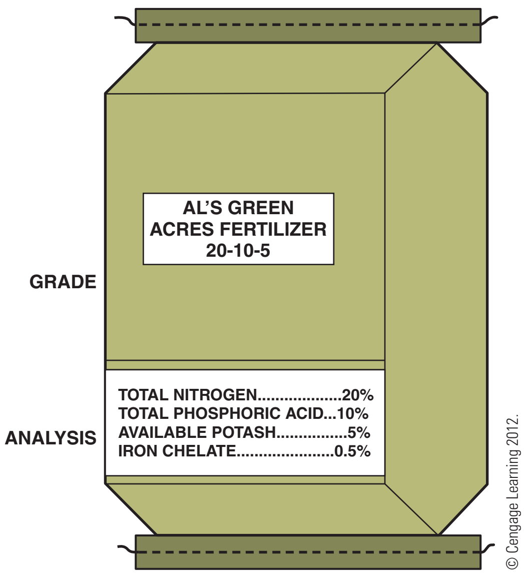


FIGURE 12-24
Mixed dry fertilizers must be labeled with the concentration of the fertilizer nutrients they contain.

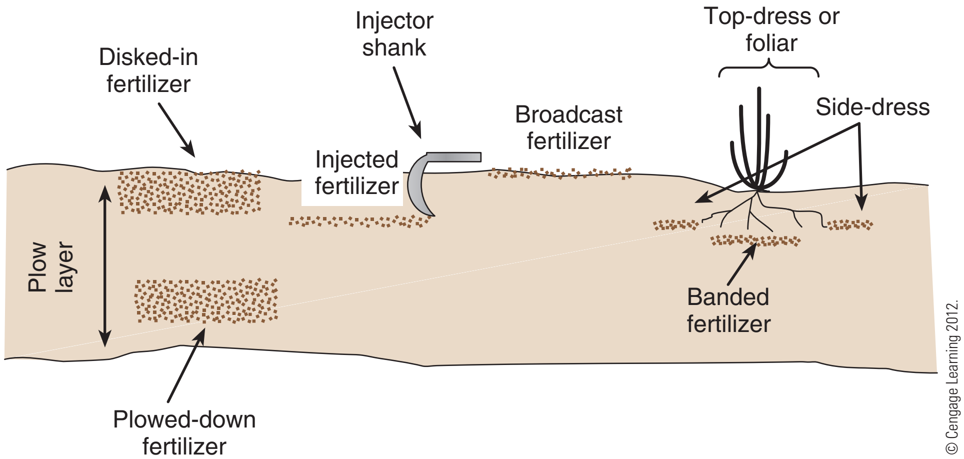


FIGURE 12-25 Application or placement of fertilizers. The simplest delivery system is to broadcast the fertilizer onto the soil surface.

- **Injection.** Injection or knifing of a fertilizer is done with anhydrous ammonia and some manures. Injection is critical for anhydrous ammonia because it enables the ammonia to react with the soil water and condense. Injection of liquid animal manure is employed to limit runoff and odors.
- **Banding.** Banding is a typical approach to fertilizer application at planting. The seeding equipment is capable of depositing a band of dry fertilizer within 2 inches (5.1 centimeters) of the seed. The fertilizer is then readily available for the seed to use after it germinates.
- **Popup fertilizers.** These fertilizers are placed in the row with the seed instead of beside the seed as in banding. Popup fertilizers are then available to the germinating seed.
- **Side-dressing.** This is an approach to fertilizing annual crops such as corn and potato after the crop has emerged. Fertilizer is deposited with specialized equipment alongside the row.
- **Fertigation.** This process fertilizes a crop by injecting the fertilizer into the irrigation water.

Best Nutrient Management Practices

Organic and inorganic fertilizers supply nutrients for plant growth and can result in economic profitability, but can have harmful effects on the environment if not used properly. Producers can ensure that their nutrient management practices have minimal environmental impact by using the following practices:

1. Test soil regularly and follow fertilizer recommendations precisely to avoid unnecessary overapplication of nutrients. All states provide recommendations for economically optimum rates of fertilizer to apply to crops.
2. Test manure before application and apply only at appropriate rates.
3. Time fertilizer and manure application to crop needs. Nutrients not used by the crop are in danger of being lost to the environment. Many crops need the most nutrients one month after planting.

4. Use the most efficient method of fertilizer application. For example, manure that is broadcast provides less nitrogen than injected manure because some of the nitrogen volatilizes into the air.
5. Combine nutrient management with soil conservation management. Reducing soil erosion will help retain nutrients in the field.
6. Incorporate green manures and perennials into rotations.

Soil Degradation

Wind, water, and ice naturally change topography through the process of geologic erosion. Many great rivers have carved deep channels in landscapes, and mighty glaciers have moved soil and deposited it thousands of miles later. Geologic erosion can be as dramatic as landslides, but most often it occurs at a slow rate. On average, soils form at about one-half inch (1 centimeter) every 100 to 400 years, which is a faster rate than geologic erosion. The widespread use of land for agriculture has accelerated the rates of soil erosion (Figure 12-26) as compared to natural processes. There is great concern that with high rates of soil degradation, we will have an insufficient soil resource remaining to meet the world's food needs in the future.

Erosion is the accelerated loss of soil through the action of wind or water. The average soil loss due to water erosion is about 3 tons/acre/year (6.7 tonnes/hectare/year), whereas about 2 tons/acre/year (4.5 tonnes/hectare/year) are lost due to wind erosion. Average losses are greater in cultivated cropland than pasture and rangeland that have continuous vegetative covers to stabilize the soil (Table 12-13). Annual soil losses vary from state to state. Water erosion is greater in areas with greater rainfall such as the eastern and southern United States, whereas wind losses are greater in the western United States where the climate is dry and high wind velocities occur (Figure 12-27).



Lynn Betts, USDA-NRCS.

FIGURE 12-26
Water erosion of soil from an agricultural field in Iowa.

TABLE 12-13

Estimated average annual loss of topsoil in tons/acre to erosion in nonfederal lands of the United States. 1 ton/acre = 2.3 tonnes/hectare. *Adapted from NRCS (2009).*

	Water erosion		Wind erosion	
	(tons/acre/year)			
	1987	2007	1987	2007
Cultivated cropland	4.0	3.0	3.6	2.5
Pastureland	1.0	0.8	0.1	0.1
CRP land	2.0	0.4	6.5	0.4

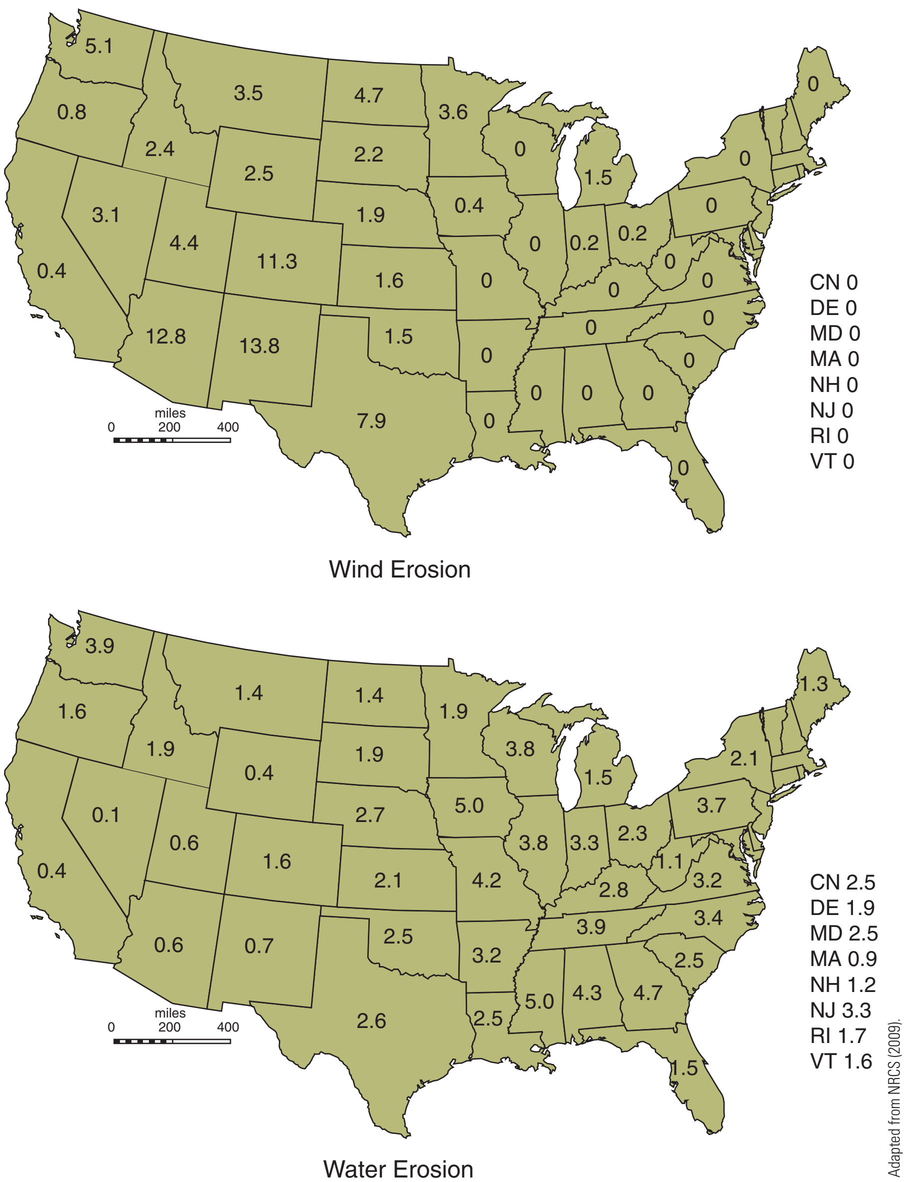


FIGURE 12-27
Average annual wind and water erosion from cropland by state in tons/acre/year, 2007. 1 ton/acre = 2.3 tonne/hectare.

With wind and water erosion, soil particles are detached and moved. With water erosion, falling raindrops disturb soil particles and surface aggregates. Flowing water then removes the soil particles. In wind erosion, the wind initially loosens coarse soil particles such as sand. Tumbling sand particles then loosen smaller silt and clay particles that become suspended in the air. Erosion is a challenge to crop production because it removes the topmost, fertile layer of soils and leaves less fertile, subsoil layers.

Reducing Soil Losses

Though water and wind erosion cannot be eliminated, they can be greatly reduced. The most important crop management strategy for minimizing both wind and water erosion is to maintain a permanent, vegetative cover over the soil. Vegetation cover prevents the initial loosing of soil particles and reduces wind and water velocity. When perennial crops cannot be maintained, leaving annual crop residues on the field also reduces erosion. Another strategy to reduce erosion is to maintain a high soil organic matter content. Soil with high organic matter content has increased soil aggregation, water infiltration, and soil particle stability. High amounts of soil organic matter can be achieved through the growth of perennial crops and the addition of crop residues. Other strategies for soil conservation include conservation tillage, crop rotation, contour tillage, strip cropping, and grass waterways and windbreaks. The federally sponsored Conservation Reserve Program that subsidizes planting of perennial vegetation such as native prairie plants provides for long-term production of the landscape. However, the land cannot be used for agricultural production.

Conservation tillage enables at least 30 percent of the crop residue to remain on the soil surface and provides a rough, uneven soil surface (Figure 12-28, Table 12-14). This practice is effective at reducing both wind and water erosion. Conservation tillage can be accomplished by using several approaches including no-till, chisel, and disk plowing. Tillage practices are described in Chapter 14.

Crop rotations that involve both annual and perennial crops provide for greater year-round ground cover and greatly reduce soil erosion (Figure 12-29). Erosion

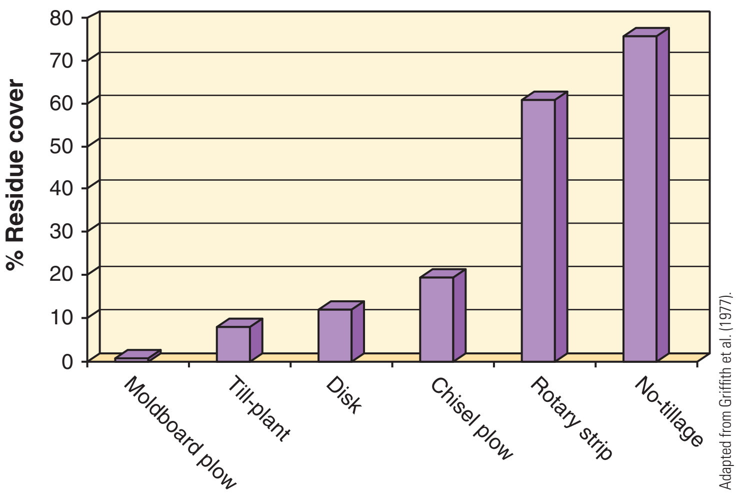


FIGURE 12-28 Effect of tillage system on residue cover in continuous corn.

TABLE 12-14

Soil erosion, nutrient, and C losses in eroded sediment from corn cultivation. *Adapted from Coyne and Thompson (2006) and Follett et al. (1987).*

	Soil erosion		Organic carbon		Organic nitrogen		Organic phosphorus	
Tillage	1000s tons	1000s megagrams	1000s tons	1000s megagrams	1000s tons	1000s megagrams	1000s megagrams	1000s tons
Conventional tillage	1,539,769	1,396,855	54,432	49,380	4453	4040	450	496
Conservation tillage	634,379	575,499	22,741	20,630	1863	1690	190	209
No tillage	481,293	436,622	17,516	15,890	1433	1300	140	154

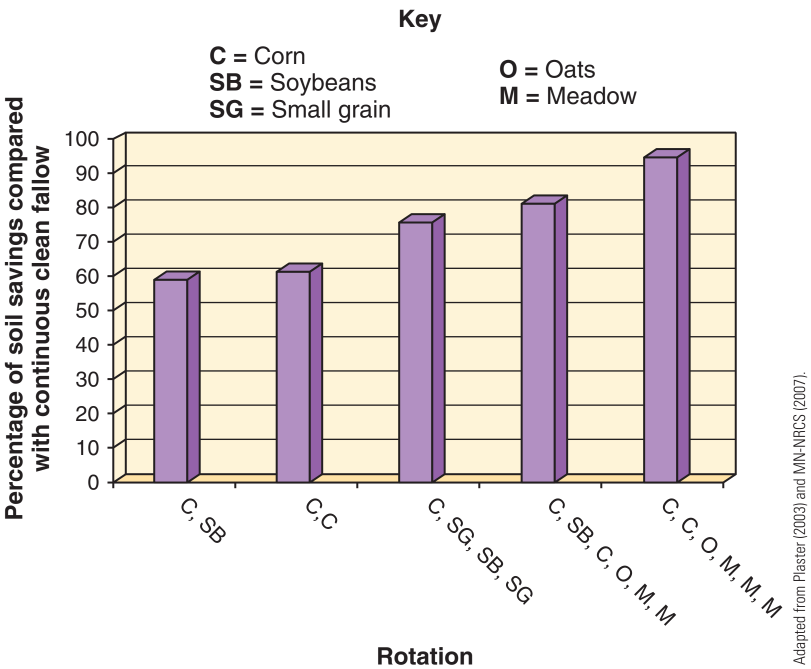


FIGURE 12-29
The effect of crop rotations on soil erosion. Increasing the time the land has perennial vegetative cover such as meadow (alfalfa) greatly decreases soil erosion.

losses are usually greatest for annual rotations such as corn-corn or corn-soybean. Adding perennial crops to such crop rotations decreases wind and water erosion.

On sloping land, crops can be grown in strips at similar elevations along the contour of a landscape (Figure 12-1). This practice is called *contour tillage* and *strip cropping*. Alternate strips of perennial and annual crops are often grown so that the perennial crop will slow down water runoff and filter out any eroded soil particles.

Grass waterways are established within fields to channel water away from the fields. The permanent grass cover reduces the flow of water and stabilizes the soil. Windbreaks, also called *shelterbelts*, are effective in reducing the wind velocity and thereby soil movement. Usually trees, shrubs, or tall grasses are planted as windbreaks.

Review Questions

1. What is a soil?
2. Describe a soil profile.
3. What are some of the important soil functions?
4. What are the three primary types of rocks in the earth's crust?
5. Identify three soil-forming factors.
6. What is organic matter composed of?
7. What is the C:N ratio, and what does it affect?
8. What are the different functions of organic matter in soil?
9. Identify at least one soil organism.
10. Explain the terms *field capacity* and *permanent wilting point*.
11. What is soil fertility?
12. What is soil texture?
13. How do different soil textures affect agricultural usage of the soil?
14. What is cation exchange capacity?
15. What are the differences between organic and inorganic fertilizers?
16. Describe the different fertilization methods.
17. What is soil erosion, and what are some ways to minimize its effect?
18. What are some best management practices for nutrient management?

Critical Thinking

1. Go to the NRCS website at http://www.nrcs.usda.gov/ and locate your state soil or another important soil in your region. What does the soil profile look like? What are its properties and best uses?
2. Why is water erosion more severe in some regions of the United States than others?
3. What types of crops typically lead to the greatest amount of soil erosion? Which types lead to the least amount of soil erosion?
4. The Universal Soil Loss Equation was developed to estimate the effect of cropping practices on soil loss. Go to the NRCS website at http://www.nrcs.usda.gov/ and identify the important factors influencing soil erosion.
5. Go to the website for the agricultural university in your state and find a source of information for fertilization of an important crop like corn, soybean, or alfalfa. What are the nitrogen, phosphorus, or potassium recommendations for an average yield of that crop in your state?

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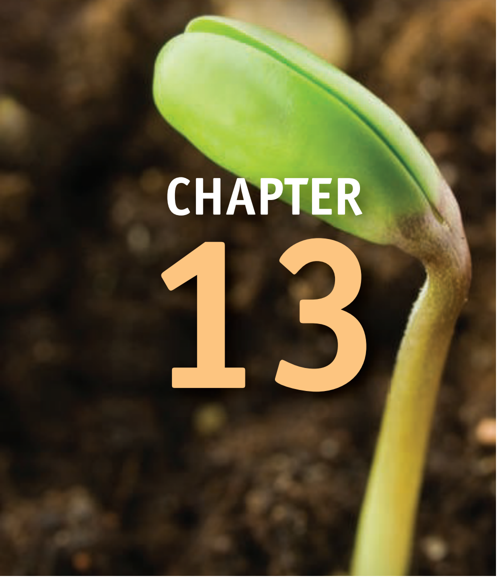
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CHAPTER 13



Cropping Systems





Key Concepts

- Continuous cropping and crop rotation are two cropping system approaches.
- Crop rotations provide several advantages compared to continuous cropping including weed control, disease and insect control, rotation effects, and reduced risks.
- Rotations including perennial legumes such as alfalfa are especially effective at reducing soil erosion and improving soil quality.
- Polyculture (intercropping) is a cropping system in which two or more crops are grown together on the same field during a growing season.
- Polycultures provide several advantages compared to monocultures including greater tolerance to stress and greater use of environmental resources.
- Living mulch systems involve planting annual grain crops into a living but suppressed perennial sod.
- Multiple cropping is the sequential production of two or more different crops from the same field each year. It allows for maximum use of the land.
- Cover cropping is a type of multiple cropping in which a cover crop is grown following the harvest of a cash crop in the spring or late summer.
- Green manure crops such as alfalfa and hairy vetch are grown for the primary purpose of plowing under to improve soil quality.
- The Conservation Reserve Program is a federally supported program aimed at promoting soil conservation, improving water quality, establishing wildlife habitat, and enhancing wetland resources.
- Riparian buffers and shelterbelts are two types of conservation plantings for agricultural landscapes.

Key Terms

agroforestry
allelopathic
alley cropping
biodiversity
conservation planting
continuous cropping
contour strip cropping
cover cropping
crop rotation
cropping system
double crop
evenness
intercropping
living mulch
mixed intercropping
monoculture

- multiple cropping
- polyculture
- richness
- riparian buffer
- rotation effect
- shelterbelt
- silvopasture
- strip cropping
- yield stability

Introduction

Cropping systems enable the management of crops so as to efficiently use the available climatic and soil resources. The cropping systems that producers use are therefore greatly influenced by the environmental conditions of a region. Socioeconomic and political factors also have a large effect on what producers grow.

Cropping systems vary in their biodiversity. **Biodiversity** refers to all the species of living organisms in an agroecosystem that we will consider a whole farm. The two components of biodiversity are **richness** (number of species or number of crops) and **evenness** (distribution or relative abundance of the individuals of a species). Increased biodiversity is considered to be healthy for agricultural landscapes because it provides resistance to crop failure due to extremes in weather, pests, or other catastrophes. Biodiversity also provides for a balance of beneficial and harmful insects and other organisms. It is possible to achieve biodiversity on a farm by using cropping systems that include crop rotations, polycultures, multiple cropping, and agroforestry.

Continuous Cropping and Crop Rotations

Continuous cropping and crop rotation are two approaches for using a land area or field over the years (Figure 13-1). With **continuous cropping**, the same crop is grown for 2 or more years on the same land. Continuous cropping is typically practiced when there are economic incentives for growing that single crop or there is a limited market for alternative crops. Continuous cropping also allows for greater specialization in terms of management, equipment, and marketing. Some crops

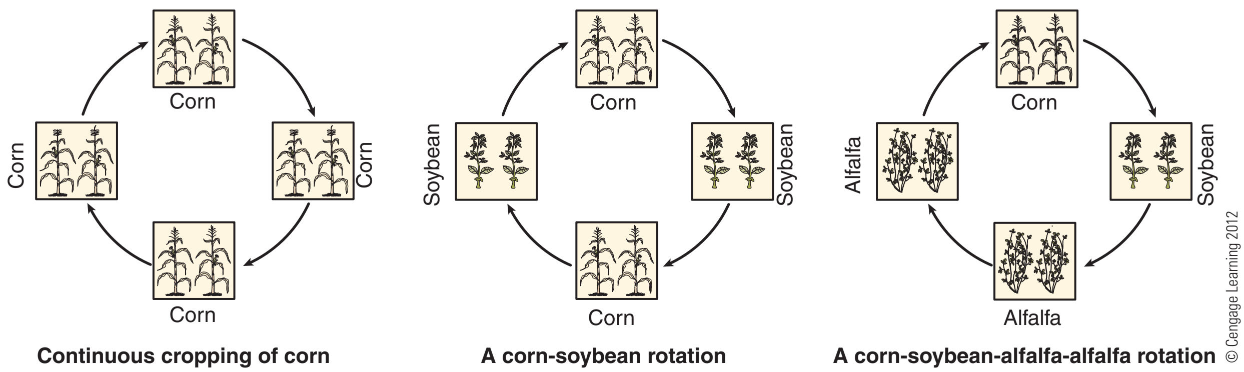


FIGURE 13-1 Continuous cropping and crop rotations are two types of cropping systems. The first example shows continuous cropping. The second and third examples demonstrate two different rotations. With crop rotations, the crops that are grown vary over the 4-year duration.

that are typically continuously cropped include wheat in the Central and Southern Plains and the Northwest, cotton in the Southwest, and corn in the Midwest.

In contrast to continuous cropping, **crop rotation** is a planned sequence of different crops grown over years on the same land. Crop rotations vary in length and diversity of crop species. The trend toward simplified crop rotations is possible with synthetic inputs of fertilizers and pesticides. Some examples of crop rotations follow:

- **Corn-soybean (2-year rotation).** This rotation is widely used in the Midwest to produce two high-value crops while still taking advantage of the benefits of rotation. Each crop has many markets. Specialized input systems (fertilizers and pesticides) have been developed to increase the efficiency of production. An incentive for growing these crops is that both corn and soybean are covered in USDA price support programs. Although soybean is a legume, its contribution of biologically fixed nitrogen is limited because much of the fixed nitrogen is removed in the grain harvest. Some scientists are concerned because excess nitrogen fertilizer leaches from the corn phase of this rotation. These crops each cover the soil for only about 6 months of the year, so the risk of soil erosion during the winter and early spring is high. The rotation length between crops is also inadequate to reduce the impact of many pests such as the soybean cyst nematode.
- **Oat/alfalfa-alfalfa-alfalfa-corn-soybean (5-year rotation).** This rotation is typical for dairy farms in the northern United States. The oat is used as a companion crop for establishment of alfalfa and provides grain and straw for livestock feeding. The alfalfa is harvested as hay or silage and stored for later feeding. The corn or soybean can be marketed or processed as feed on the farm. This rotation is also largely nitrogen self-sufficient because the alfalfa (through biological nitrogen fixation) provides the nitrogen to meet the needs of the following corn crop. Mixing perennial and annual crops also provides for a break in the weed cycles, reducing infestations of weeds.
- **Sugar beet-soybean (or dry bean)-wheat (or corn) (3-year rotation).** Sugar beet is the most valuable crop in this rotation, which is designed to reduce disease. Depending on their relative economic value, either wheat or corn may be included in the rotation.
- **Oat/red clover (or alfalfa)-corn-soybean (3-year rotation).** This rotation is a modified version of the corn-soybean rotation that produces plow-down legume nitrogen for the corn crop. Oat is used as a companion crop and is harvested for grain and straw. Following harvest of the oat, the red clover regrows and then is plowed under in the fall. This rotation is used by producers who do not need a forage crop to feed livestock, but who do need the legume nitrogen.
- **Potato-soybean-wheat (3-year rotation).** This rotation is used for potato production in the Midwest and Idaho. Depending on the market value, soybean can be replaced by dry beans, and wheat can be replaced with field or sweet corn.
- **Winter wheat-grain sorghum-fallow (3-year rotation).** This rotation is used in the central Great Plains region, where conditions are too dry for uninterrupted annual cropping. Fallowing (see Chapter 10) provides for storage of soil moisture and weed control to maximize yield of the wheat crop.

- **Wheat-fallow (2-year rotation).** This rotation is used for winter and spring wheat production in semiarid regions of North Dakota, Montana, and Washington (Figure 13-2). When favorable market conditions exist, peas replace fallow. Peas are seeded early in the spring and have a low water use.
- **Cotton-peanut (2-year rotation).** This rotation is used in cotton-producing regions of the South and Southwest. For many years, cotton was grown exclusively in monoculture in suitable areas, exhausting the soil and available resources. The addition of a legume adds nutrients back into the system and breaks cycles of pest and disease infestation. Interestingly, George Washington Carver (1864–1943) advocated for peanut to be grown in cotton-producing areas after soils became depleted in the early 1900s.
- **Cotton-sorghum (or wheat) (2-year rotation).** This rotation is used in areas such as the southern plains that are too dry to support corn production. Cotton is the most valuable crop in this rotation, but sorghum is also a valuable livestock feed in drought-prone areas.


Tim McCabe, USDA-NRCS.

FIGURE 13-2
An example of fallowing (resting the soil). Divided slope farming is used to reduce erosion rates in Washington's Palouse region. In this method of planting, half a hillside is left in the previous year's crop residue, and the other half is planted with a new crop. The areas are rotated each planting season.

The advantages of rotations are greatly influenced by the number, type, and sequence of crops in the rotation. Greater diversity of crops within a rotation increases the advantages of crop rotation compared to continuous cropping. It is especially advantageous to include crops from different plant families (e.g., grasses vs. legumes) and with different life cycles (annual vs. perennial). A summary of the advantages of crop rotations includes the following:

- **Weed control.** Switching crops helps break weed cycles and reduces weed populations. For example, harvesting perennial crops such as alfalfa for two or more years reduces annual weed seed production and kills some perennials such as Canada thistle by depleting their root reserves.
- **Disease and insect control.** Rotations remove the hosts for diseases and insects (Table 13-2). For example, soybean cyst nematode populations are greatly reduced by long-term diverse rotations that limit the host crops in the rotation (Table 13-3). Perennials that provide dense, continuous ground cover can also provide habitat for birds and beneficial insects that consume harmful insects.

The Morrow Plots

The Morrow Plots, established in 1876 at the University of Illinois at Urbana–Champaign, is the oldest cropping-systems experiment in the United States. The site that is now less than one acre in size was designated a National Historical Landmark by the federal government on September 12, 1968. The experiment is named after G. E. Morrow, the first dean of the College of Agriculture who wanted to show the effect of cropping on the long-term productivity of the Illinois tallgrass prairie soils. The initial experiment compared three systems: continuous corn, corn-oat or soybean, and corn-oat-clover hay. Initial results showed that the rich prairie soils could become unproductive because of depletion of nutrients when crops were harvested. The experiment also showed the value of crop rotations in maintaining crop productivity. Results collected in 1997, after over 100 years of the initial rotations being without supplemental fertilization, showed that continuous corn yielded 54 bushels per acre; the corn in the corn-soybean rotation yielded 94 bushels per acre; and the corn in the corn-oats-clover rotation yielded 110 bushels per acre. Fertilization with nitrogen and other recommended nutrients increased continuous corn yield to 151 bushels per acre, to 191 bushels per acre in the 2-year sequence, and to 200 bushels per acre in the 3-year sequence.

The Morrow Plots have been a valuable field laboratory to study the impact of long-term crop production practices on soil carbon, a topic of recent interest because of the role of carbon in global warming. A team of researchers studied the impact of crop rotation and fertilization on changes in soil organic carbon content (Table 13-1). They found that 50 years of synthetic fertilizer application and tillage, even with incorporation of crop residue (stover and straw), decreased soil carbon.

TABLE 13-1

Effect of nitrogen fertilization on soil organic matter in Morrow plots, 1955–2005. *Adapted from Khan et al. (2007).*

		Soil organic carbon			
		1955		2005	
Rotation	Fertilizer	mg/ha	tons/ac	mg/ha	tons/ac
Corn-corn	None	94.3	42.1	98.0	43.7
	NPK*	94.3	42.1	94.0	41.9
Corn-soybean	None	117.5	52.4	111.9	49.9
	NPK	117.5	52.4	112.3	50.1
Corn-oats-hay	None	121.2	54.1	109.8	49.0
	NPK	121.2	54.1	116.4	51.9

*NPK indicates nitrogen, phosphorus, and potassium fertilizers were applied.

TABLE 13-2

Pests that can be reduced or controlled through rotation. *Adapted from Peel et al. (1998).*

Pest	Major crops affected
Bacterial blights	Wheat, barley, grasses, rye, corn
Common root rot	Wheat, barley, grasses
Corn ear mold	Corn
Corn root worm	Corn
Corn smut	Corn
Ergot	Rye, wheat, grasses
European corn borer	Corn
Flax rust	Flax
Flax wilt	Flax
Fusarium	Small grains
Gray leaf spot	Corn
Net blotch	Barley
Northern corn leaf spot	Corn
Pasmo	Flax
Phoma	Sunflower
Phytophthora	Soybean, potato
Rhizoctonia	Sugar beet, alfalfa, potato, soybean, others
Scab	Wheat, barley, corn, rye
Sclerotinia (white mold)	Sunflower, dry beans safflower, soybean, potato, canola
Septoria	Wheat, barley
Soybean cyst nematode	Soybean
Sunflower rust	Sunflower
Tan spot	Wheat, durum
Verticillium wilt	Potato, sunflower, safflower, alfalfa

- **Increase in soil fertility and soil quality.** Crop rotations that include nitrogen-fixing legumes such as alfalfa and soybean can add nitrogen to the soil for the growth of subsequent crops (Figure 13-3). On most soils, legume nitrogen is sufficient to supply the nitrogen requirements of a subsequent corn crop. In addition, perennial crops that do not require annual tillage result in an increase of soil organic matter that is related to enhanced soil quality (Table 13-4).
- **Reduced soil erosion.** Rotations that include perennial legumes and grasses that provide year-round ground cover have dramatically increased water infiltration and reduced soil erosion compared to row cropping (Table 13-5).

TABLE 13-3

Rotation and occurrence of soybean cyst nematodes on organic farms in Minnesota, 2006. The shorter rotations had higher soybean cyst nematode eggs. Rotations with soybean every other year or every two years had egg counts above the level (500/cc) at which crops are damaged. *Adapted from Chen et al. (unpublished data).*

Rotation	SCN (eggs/100cc)
Soybean every other year	3657
Soybean every two years	1306
Soybean every three years	496
No soybean	0

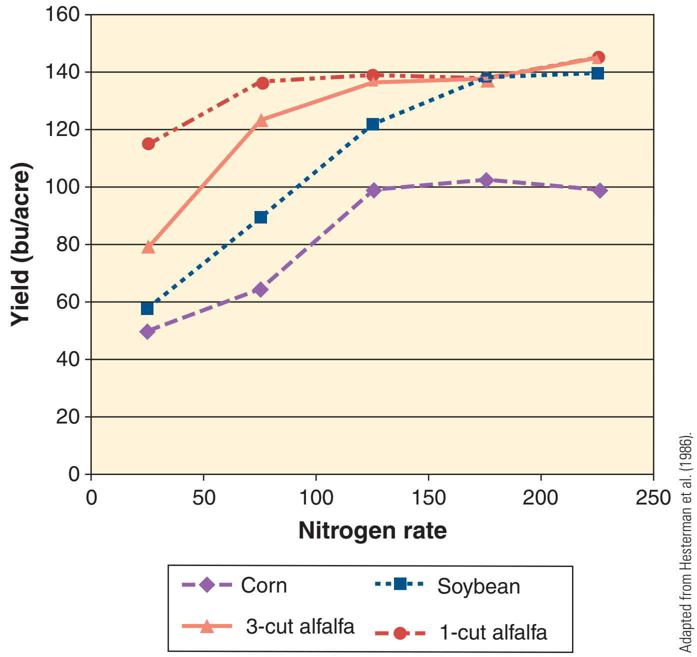


FIGURE 13-3 Nitrogen fertilizer (in pounds/acre) and rotation effects on corn yield following corn, soybean, or alfalfa. Corn yield is greater following alfalfa and soybean than corn following corn (continuous cropping). Alfalfa is superior to soybean except at the high nitrogen fertilizer rates. 1 bushel/acre = 53 kilograms/hectare. 1 pound/acre = 1.13 kilograms/hectare.

- **Rotation effects.** In addition to the beneficial effects due to enhanced soil fertility and pest control, unknown **rotation effects** occur that increase the yield of subsequent crops.
- **Less risk.** An increased diversity of crops growing on the same farm provides the potential for multiple revenue streams. Multiple crops also reduce risk should a single crop fail due to disease or drought. In Table 13-6, the continuous corn rotation is only profitable when high rates of nitrogen are applied. Adding either soybean or multiple years of alfalfa to rotation increases the return compared to unfertilized corn.

TABLE 13-4

Soil quality indicators for various rotations in Iowa. Measurements were taken during the first corn crop after each rotation. Bulk density is a measurement of mass per unit of volume; soils with higher organic-matter content will have lower bulk densities. *Adapted from Karlen et al. (2006).*

Rotation	Bulk density g/cm3	Water-stable macro aggregation %	pH	Total organic carbon g/kg
Corn-corn	1.14	44.8	6.73	33.4
Corn-soybean	1.11	45.2	6.84	32.7
Corn-corn-corn-oat/legume	1.08	52.2	6.12	36.6
Corn-corn-oat/legume-meadow	1.00	57.1	6.22	38.3
Corn-oat/legume-meadow-meadow	1.00	60.9	5.55	41.7

TABLE 13-5

The effect of rotation on relative soil loss. Row crops are planted in rows usually 30 inches apart, whereas meadow crops like alfalfa and grasses are seeded by broadcasting. The C-factor is the ratio of soil loss from an area with specified cover to that from an identical area in tilled continuous fallow. Increasing the proportion of perennial crops in the rotation dramatically reduces soil erosion. *Adapted from Papendick and Elliot (1984).*

Rotation	% row crop	C-factor
Corn-soybean	100	0.43
Corn	100	0.35
Corn-corn-oat-meadow	50	0.12
Corn-corn-oat-meadow-meadow	40	0.09
Corn-oat-meadow	33	0.06
Meadow	0	0.04

- **Recycling of nutrients.** Because of the production of crop species with different rooting systems, there is greater opportunity for recycling of nutrients. Alfalfa and perennial grasses have been shown to be effective at reducing the nitrogen loss from tile drainage systems (Table 13-7).

TABLE 13-6

Average annual dollar-per-acre returns to land by cropping system and nitrogen rate at Lancaster, Wisconsin, 1990 to 2004. Nitrogen was applied to corn only. *Adapted from Stanger et al. (2008).*

	N rate		Average return	
Rotation	lbs/acre	kg/hectare	$/acre	$/hectare
Corn-corn	0	0	−85	−211
	200	224	59	147
Corn-corn-corn-alfalfa-alfalfa	0	0	32	78
	200	224	62	152
Corn-corn-oat/alfalfa-alfalfa-alfalfa	0	0	73	181
	200	224	83	205
Corn-soybean	0	0	87	216
	200	224	111	275
Corn-soybean-corn-oat/alfalfa-alfalfa	0	0	79	194
	200	224	88	218

TABLE 13-7

The effect of cropping systems on drainage volume and nitrate-N losses in subsurface tile drainage during a 4-year period (1990–1993) in Minnesota. *Adapted from Randall et al. (1997).*

	Total drainage		Nitrate-N Loss	
Cropping system	inches	centimeters	pounds/acre	kilograms/hectare
Continuous corn	30.4	77.2	31.4	35.2
Corn-soybean	35.5	90.2	29.4	33
Soybean-corn	35.4	89.9	29.2	32.7
Alfalfa	16.4	41.7	1.0	1.1
Conservation Reserve Program	25.2	64	0.6	0.7

Continuous Corn

In 2007, the demand for corn for ethanol conversion drove grain prices to record highs. Anticipating large profit potential, producers grew over 90 million acres (36 million hectares) of corn in 2007. Although in recent years nearly 80 percent of corn has been grown in rotation with soybean or other crops, in the future, many more acres will likely be produced by continuous cropping. Many agronomists expect at least a 10 percent grain-yield loss for corn following corn versus corn following soybean. This prediction is based on long-term research like that from Hicks and Hoverstad (2007) at the University of Minnesota that showed 12 bushel/acre (753 kilogram/hectare) greater yield for corn following soybean than for corn following corn.

As discussed in previous chapters, from an ecological and environmental standpoint, continuous cropping of corn is undesirable. The continuous corn system may be economically justified because of the high value of corn grain, but the lack of crop diversity may put our food supply in jeopardy. In addition, the high levels of synthetic inputs that substitute for rotation effects may have environmental consequences. Even now scientists are concerned about the excess loss of nitrogen fertilizers and soil sediment from the continuous corn system.

Monoculture versus Polyculture

Monoculture systems involve growing a single crop within a field during the growing season (Figure 13-4). Most important grain crops such as corn, soybean, rice, and wheat are grown in monoculture. Monoculture production systems simplify crop management and allow for concentration of efforts and resources on maximizing economic return from a single crop. The advantages of monoculture include the following:

- Machinery specialized for the crop can be used to maximize efficiency of crop planting and harvest.
- Chemicals such as herbicides, insecticides, and fungicides can be used to target the specific weed, insect, and microbial pests of the monocrop.
- Fertilizer systems can be developed to meet the nutrient needs of the crop by applying the nutrients at specific developmental stages.
- Specialized varieties are developed to efficiently use light, moisture, and other environmental resources.
- With monocultures, maturity and dry down of all plants within a variety is synchronized. This allows for a single harvest with reduced loss of grain due to spoilage.



FIGURE 13-4
A soybean monoculture in Redwood County, Minnesota. This field is planted in a rotation, and the soybean has followed corn.



FIGURE 13-5
A polyculture of alfalfa mixed with reed canary grass. This mixture will be harvested for hay when it is mature.

Polyculture is the growing of two or more crops together on the same piece of land during a growing season (Figure 13-5). Polyculture allows for spatial diversification of plant species. It provides greater opportunity to efficiently use soil and environmental resources compared to monoculture. Polyculture is also called **intercropping**. Polyculture systems can be challenging to manage because species growing together compete and have diverse resource needs. Types of intercropping include mixed intercropping and strip cropping.

Polycultures have the potential to provide several advantages compared to monocultures.

- Polycultures have greater tolerance to environmental and pest stress, and they provide insurance against total crop failure. Should one of the crops die, the other species can still produce yield. This is sometimes called **yield stability**.

- Polycultures of woody crops and pastures in silviculture (tree agriculture) systems provide for income diversification by providing short-term and long-term income, as well as products for different markets.
- Polycultures with plants that have different nutrient needs and rooting characteristics have the potential for greater use of light, water, and nutrient resources. In addition, they have greater overall productivity per acre. Polycultures of nitrogen-fixing legumes with annual or perennial grasses are less dependent on nitrogen fertilizer inputs.

Mixed Intercropping

One type of polyculture is **mixed intercropping**, where two or more crops are grown together at random. In natural settings and premodern agriculture, most plants naturally grew together in mixed polycultures. Native Americans intercropped corn, beans, and squash. The corn plants grew upright, the squash used the corn for climbing, and the beans provided nitrogen (through fixation) to the corn plants. Polycultures are still used today, although they fit best in forage production systems where the individual species can be harvested together. Some examples include the following:

- **Mixtures of native plants used in prairie restoration projects.** Native grasses, forbs, and legumes are planted together in an attempt to replicate native plant ecosystems. Planting a diversity of plants will allow for establishment of plant species adapted to the variation in soil and microclimate conditions within the landscape. These mixtures provide ecosystem services such as soil stabilization, carbon sequestration, and wildlife habitat, as well as forage for grazing livestock. It has also been proposed that native plantings be harvested and used as biofuels (see Chapter 5). See Table 13-8 for examples of native plant mixtures.
- **Hay mixtures used in the northern United States.** These mixtures are simpler than the prairie restoration mixtures and usually contain one or two perennial legumes with several perennial grasses. Mixing grasses with legumes speeds the drying of the cut forage and provides for greater year-round cover of the soil. These mixtures can also be harvested by grazing animals. Some examples of hay and pasture mixtures for Iowa show the use of diverse species for unique soil conditions (Table 13-9).
- **Spring-planted companion crops.** A companion crop such as oat is used to establish small-seeded forage crops such as alfalfa (Figure 13-6). The fast-growing and vigorous annual crops provide ground cover and weed control for the slow-growing forages. The small grains are harvested for grain and straw at maturity, and the forage seedings become established and regrow following harvest of the grain crop. However, companion crops can potentially reduce alfalfa-seeding yields through competition with small alfalfa plants (Table 13-10).
- **Spring-planted wheat and pea mixtures.** These mixtures can be harvested for grain or for silage before the grain is ripe. Livestock use the wheat grain as an energy source and the pea as a protein source.
- **Oat or barley and pea mixtures.** The two species are sown together in early spring and harvested when mature for grain. This supplies a high-protein mixed grain for livestock feeding.

TABLE 13-8

Native species mixture recommended for restoring native prairies in the Conservation Reserve Program in Wisconsin. *Adapted from Shooting Star Native Seed Company (2010).*

	Wet prairie mesic mix for CRP planting rate 4.8 lbs/acre (5.4 kg/hectare)		
	Scientific name	Common name	% of mix
Grasses	*Andropogon gerardii*	Big bluestem	10.4
	Carex vulpinoidea	Fox sedge	5.2
	Elymus canadensis	Canada wildrye	20.9
	Glyceria striata	Fowl mannagrass	5.2
	Panicum virgatum	Switchgrass	20.9
	Sorghastrum nutans	Indian grass	15.6
	Spartina pectinata	Prairie cord grass	10.4
Wildflowers	*Asclepias incarnata*	Swamp milkweed	1.3
	Desmodium canadense	Showy ticktrefoil	2.6
	Eupatorium maculatum	Joe pye weed	0.7
	Eupatorium perfoliatum	Boneset	0.7
	Silphium perfoliatum	Cup plant	2.6
	Verbena hastata	Blue vervain	1.3
	Vernonia fasciculata	Ironweed	0.7
	Veronicastrum virginicum	Culver's root	0.3
	Zizia aurea	Golden alexander	1.3

TABLE 13-9

Forage seed mixtures recommended for Iowa. *Adapted from Barnhart and Sternweis (2009).*

		Seeding rate	
		lbs/acre	kg/hectare
Soil type			
Moderately to well-drained, neutral, fertile soils	Alfalfa	8–10	9–11
	Smooth bromegrass	6–8	6.7–9
	Orchard grass	4–6	4.5–6.7
	Reed canary grass	6–8	6.7–9
	Timothy	3–4	3.4–4.5

(Continued)

TABLE 13-9 (Continued)

Forage seed mixtures recommended for Iowa. *Adapted from Barnhart and Sternweis (2009).*

		Seeding rate	
		lbs/acre	kg/hectare
Somewhat poorly to poorly drained, slightly acid soils	Red clover	6–8	6.7–9
	Smooth bromegrass	6–8	6.7–9
	Orchard grass	4–6	4.5–6.7
	Reed canary grass	6–8	6.7–9
	Timothy	4–5	4.5–5.6
Somewhat poorly to poorly drained soils	Red clover	6–8	6.7–9
	Ladino clover	1/2	0.6
	Orchard grass	4	4.5



Craig Sheaffer, University of Minnesota.

FIGURE 13-6
Establishing alfalfa by using an oat companion crop. The companion crop reduces soil erosion and suppresses weeds while the alfalfa is getting established.

TABLE 13-10

Grain and alfalfa yields for alfalfa spring-seeded with various companion crops in southern Minnesota. *Sheaffer (unpublished data).*

	Grain yield		Alfalfa yield	
Cover crop	bushels/acre	kg/hectare	tons/acre	tonnes/hectare
Spring oat	84	3013	0.4	0.9
Spring wheat	48	3228	0.5	1.1
Spring barley	78	4196	0.4	0.9
Field pea	54	3632	0.2	0.4
Flax	19	1278	0.4	0.9
Herbicide, no cover crop	—	—	3	6.7



FIGURE 13-7
Alley cropping of a hay crop with trees.

- **Agroforestry.** This is a type of system where trees or shrubs are grown for harvest alongside other crops. Agroforestry is discussed later in this chapter.
- **Alley cropping.** This is a type of agroforesty and is a method where trees are grown in rows with annual or perennial crops between the trees (Figure 13-7).
- **Silvopasture.** This is a type of agroforestry system that combines trees with pastures for livestock utilization. The trees are managed for production of wood for multiple uses.

Strip Cropping

Strip cropping is a polyculture strategy that involves growing crops in monocultures, in adjacent strips planted within a field. The width of the strip can vary depending on the available machinery. Strip cropping can involve alternate rows of annual crops that are usually harvested at different times. A common form of strip cropping is **contour strip cropping** for soil conservation on sloping erodible lands (Figure 13-8). In this strategy, annual row crops are grown in alternating strips with perennial crops such as alfalfa. The perennial alfalfa crop reduces erosion by increasing water absorption and decreasing water runoff from the landscape.

Living Mulches

Living mulch systems involve planting annual grain crops into a living but suppressed perennial sod that can recover following harvest of the grain crop. The living mulch provides year-round ground cover for soil conservation and weed suppression. Legume living mulches can also provide biologically fixed nitrogen to the grain crop. An example of a living mulch system that is used in Wisconsin employs kura clover, a perennial legume, as the living mulch crop (Figures 13-9 and 13-10). Corn is planted into kura clover strips that have been killed using a herbicide. When corn is harvested, kura clover, a rhizomatous species, can regrow into the space where the corn was grown. The kura clover can then be used for grazing in



Tim McCabe, USDA-NRCS.

FIGURE 13-8
Contour strip cropping of corn, soybean, and alfalfa. Soybean is planted on the flat area adjacent to corn. Alfalfa provides permanent ground cover and reduces soil erosion. After 3 years alfalfa will be rotated to corn and corn to alfalfa.



Ken Albrecht, University of Wisconsin.

FIGURE 13-9
A kura clover-corn living mulch system. The corn is seeded into killed strips of previously established kura clover.

the fall and in the following year. Other legumes such as crown vetch and alfalfa can also be used for living mulches. Despite their promise, living mulch systems have been used only to a limited extent because of the management challenges. The living sod must be suppressed so as to limit early competition for moisture and light with the interseeded grain crop, but the suppression must be controlled to enable the recovery of the mulch crop. Successful living mulch systems depend on specialized no-till and spraying equipment, as well as strategic use of herbicides and tillage.



FIGURE 13-10
A kura clover-corn living mulch system. The kura clover is regrowing following harvest of the corn.

Multiple Cropping Systems

Multiple cropping is the sequential production of two or more different crops from the same piece of land each year (Figure 13-11). Multiple cropping provides for maximum use of the land and the environment for crop production. Multiple cropping is most often practiced in regions with a long growing season. With the mild winters of the southern United States, crops can be grown continuously. For some areas, crop varieties have been developed with early maturity to allow for a shorter time from planting to harvesting. In more northern climates with short growing seasons, multiple cropping is not normally practiced. Most multiple cropping systems use both summer and winter annual crops. Multiple cropping systems are called *double* (two crops) or *triple* (three crops) based on the number of crops that are grown. For example, a **double cropping** is practiced in Illinois,

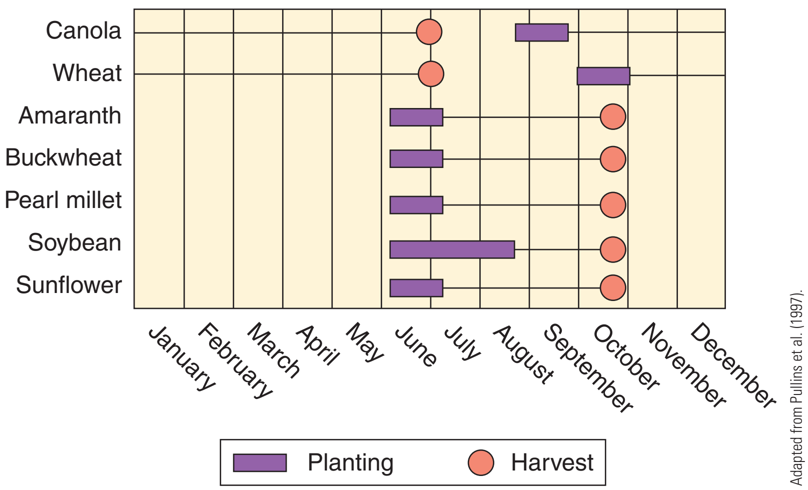


FIGURE 13-11
Examples of the timing of planting and harvesting for two winter crops and five summer crops that can be used in a double-crop system.

where wheat or barley are double cropped with soybean or corn varieties that mature in a short period of time. The wheat or barley is planted the previous fall, harvested for grain in late June, and then early maturity soybeans or corn are planted. Soybeans and corn are then harvested in late fall.

Cover Crops

Cover cropping is a type of multiple cropping system in which a crop is introduced during or following harvest of the cash crop. Cover crops can be used to cover the soil during the winter months between annual grain crops (Figure 13-12), or they can be planted in the summer after the harvest of a cool-season crop. Before the next crop is seeded, these cover crops are killed before maturity by mowing, tillage, rolling, or herbicide (Figure 13-13). Cover crops are grown for several reasons.



Jeff Vanuga, USDA-NRCS.

FIGURE 13-12
Seeding of corn into a killed barley cover crop.



USDA-ARS.

FIGURE 13-13
Flail-mowing a rye and vetch cover crop that will serve as a weed barrier for organic crop production.

- To protect the soil from wind and water erosion after an annual crop such as corn or soybean is harvested and before the next crop is planted
- To absorb excess fertilizer nutrients from the soil
- To enhance soil fertility for subsequent crops through the addition of atmospheric nitrogen (legume nitrogen fixation) or organic matter
- To reduce weed growth
- To provide habitat for insects and animals that consume weed seeds
- To control soil moisture levels. Cover crops can dry up wet soils. Alternatively, if their residues are retained on the soil surface, they can conserve soil water. Depletion of soil water by cover crops can be detrimental where rainfall is limited.

Examples of cover crops are as follows:

- **Winter rye.** This is the most winter-hardy small grain and will overwinter throughout the United States, regrowing in the spring. It is very effective in the uptake of residual nitrogen fertilizers and, in the north, is frequently used as a winter cover crop when planted following harvest of soybean or corn (Figure 13-14). Rye is also **allelopathic** (meaning, it has chemical compounds that inhibit some plants' growth) and can suppress weeds in subsequent crops.
- **Hairy vetch.** This is a winter-hardy annual legume that can protect the soil and contribute nitrogen for growth of a subsequent corn crop. It is typically planted by early September in the north, and later at southern latitudes.
- **Crimson clover and berseem clover.** In the southeastern United States, crimson clover and berseem clover are used as winter annual cover crops. They are seeded in the fall and used as a nitrogen source for the following season's crop. These clovers may or may not winter-kill depending on the winter temperatures of a region.
- **Buckwheat.** This is a fast-growing cover crop that is effective at smothering weeds. It is typically used as a summer annual. It can be planted in the spring or summer after harvest of an early-seeded crop such as peas or a winter small grain such as barley. Dense stands of buckwheat are effective at weed suppression. Buckwheat also is a good scavenger crop for uptake of phosphorus on low-fertility soils.



Adapted from Feyereisen et al. (2006).

FIGURE 13-14 Rate of nitrogen loss under winter rye for several planting dates. Depending on the planting date, winter rye can reduce nitrogen leaching by up to 45 percent in a corn-soybean rotation.

- **Forage and oilseed radish.** These are typically used as fall/winter cover crops, but can also be planted in the spring. Forage radishes seeded in August in Michigan can have root yields as high as 2 tons/acre (4.5 tonnes/hectare) and herbage yields of over 4 tons/acre (9 tonnes/hectare) (Ngouajio and Mutch, 2004). They have fast growth and have large roots that can penetrate 12 inches (31 cm) into the soil, thus relieving compaction of the soil and providing aeration. These radishes normally winter-kill and their residue is left for the following spring. The radishes suppress weeds by vigorous competition and by production of glucosinolate compounds in the herbage that poison weed seedlings. Forage radish is also known as *daikon* and is used as a vegetable.

No-till Cover Crop System for Organic Systems: Roller-crimper

Winter cover crops are usually winter annuals such as winter rye or hairy vetch that are planted in the fall and are actively growing the following spring. Because they are annuals, once they flower in the spring, they will subsequently die. However, when another crop needs to be planted the same season, producers usually cannot wait until the cover crop naturally senesces and so the cover crop must be killed first. One option used in conventional systems is a no-till winter cover-cropping system. Herbicides are used to kill the cover crop before no-till drilling of grains into the cover-crop mulch.

In organic agriculture (see Chapter 18), farmers cannot use synthetic herbicides, so they must utilize other options. Moldboard plowing can be effective in controlling cover crops at any stage of cover crop growth, but it is damaging to the soil structure. Consequently, an organic variation on the no-till cover crop system has been developed by the Rodale Institute (http://www.rodaleinstitute.org/). Their method uses a roller-crimper to mechanically kill the cover crop without disturbing the soil. Mounted on the front or back of a tractor, the roller-crimper apparatus consists of a heavy roller with blades that crimps and flattens the cover crop, which kills it and leaves behind a thick layer of mulch (Figure 13-15). Simultaneously, the next crop can be planted into the mulch using equipment designed for high residue. The crop then grows up through the decomposing mulch (Figure 13-16).

Benefits of the roller-crimper system include weed suppression by the mulch, building soil organic matter, preserving soil structure through reduced tillage, and conserving moisture. Organic producers can gain time and money because they do not have to plow or perform weed control operations early in the season. The soil is protected over winter and the soil structure is preserved because of the reduced tillage. In addition, legumes such as hairy vetch can supply nitrogen to the main crop.

One disadvantage of the system is that the roller-crimper operation must be timed at the correct stage of cover crop growth, which is generally during anthesis for a grass such as rye, or early flowering for a legume like hairy vetch. If performed too early, the cover crop will not be



FIGURE 13-15 A roller-crimper attached to a tractor.



FIGURE 13-16 Soybean growing in a mulch of winter rye.

terminated and will regrow. This can lead to the cover crop competing with the primary crop and to poor yields. Additionally, in cooler regions such as Minnesota, the mulched soil may take much longer to get warm or remain too wet, setting back development of warm-season crops such as corn or soybean. However, the roller-crimper system has been successful in other parts of the country, particularly those that are warmer and have longer growing seasons.

Green Manure Crops

Green manure crops are grown for the primary purpose of plowing under to improve the soil quality through the addition of organic matter and nutrients. As the name *green* implies, many types of grasses and legumes can be plowed under when green and succulent (Figure 13-17). Legume green manure crops are especially effective because they can add biologically fixed nitrogen for subsequent crops. Green manuring with lupines, vetch, peas, and clover was popular in ancient Greek and Roman agriculture. In the United States, alfalfa and sweet clover were used extensively as green manure crops before the widespread use of synthetic fertilizers. They were grown for a single season without harvest and plowed under after one year. Some farmers use sweet clover and alfalfa to grow their own nitrogen for crop production (Table 13-11). Currently, hairy vetch, crimson clover,



David L. Hansen, University of Minnesota.

FIGURE 13-17
Plowing under a 1-year-old alfalfa stand as a green manure crop. Alfalfa can supply all the nitrogen needed by a subsequent corn crop.

TABLE 13-11

Forage and nitrogen production in 1 year from spring-seeded legumes. Legumes were not harvested. *Adapted from Sheaffer and Seguin (2003).*

	Forage yield		N yield	
Legume	tons/acre	tonnes/hectare	pounds/acre	kilograms/hectare
Alfalfa	2.3	5.2	30.0	33.6
Red clover	2.8	6.3	32.4	36.3
Sweet clover	2.7	6.1	50.2	56.3

red clover, and winter rye are used as winter-annual green manure crops. The concepts of cover cropping and green manuring are linked because most cover crops can be incorporated as green manures.

Agroforestry Cropping Systems

Agroforestry is a type of agricultural system where trees or perennial shrubs are grown for harvest alongside other annual or perennial crops or grazing livestock. Agroforestry can generate additional sources of income, be used on marginal lands on the farm, and serve ecological and environmental functions such as carbon fixation, providing species habitat, and protecting critical soil and water resources. Tree farms, nut plantations/orchards, or woodlots can be combined with annual and perennial cropping systems. Two types of agroforestry systems are alley cropping and silvopasture.

Alley Cropping

In an **alley cropping** system, trees are grown in rows with other crops between them in the inter-row area (see Figure 13-7). The alleys need to accommodate the size of mature tree crops so enough light can reach the alley crop without shading. Additionally, crop choices and cropping systems could change according to the height and canopy development of the tree or shrub. The alley between the trees also needs to be wide enough to accommodate harvesting, tillage, or other mechanical equipment. The trees or shrubs act as a wind and water break between the crop, additionally protecting valuable soil and water resources for the annual crop. An example of an alley cropping system would be growing hardwoods—such as walnut or oak—that are harvested for wood in rows alongside a perennial alfalfa hay crop grown between the trees. Another example is growing hybrid poplar, which is harvested as a bioenergy crop, between sections of corn, soybean, or other annual grain crops.

Silvopasture

Silvopasture is a type of agroforestry system that combines trees with pastures for livestock utilization. The trees and livestock must both be intensively managed for production; the livestock provide income while the trees mature. Trees or shrubs can be utilized for timber, nut or fruit crops, or other uses. Tree crops that work best in silvopasture are rapidly growing, marketable, and hardy to numerous stresses. Grazing by animals usually commences after a few years to allow the trees to adequately mature so that grazing, foot traffic, or trampling will not damage them. The trees or shrubs additionally provide shade and shelter for the livestock. An example of silvopasture is growing Christmas trees with a legume or grass pasture that is grazed by cattle or sheep during the development of the trees.

Conservation Plantings

A bird's-eye view of agricultural landscapes shows that in many regions, cropping systems lack diversity. This is related to ongoing farm policy programs, as well as the availability of markets for agricultural products. For example, in much of the traditional Corn Belt, more than 95 percent of the acreage is planted with corn and soybean. However, as shown in Figure 13-18, there are opportunities to diversify the landscape through strategic placement of crops as well as **conservation plantings**.

Federal and state governments fund several programs that aim to improve landscape diversity and increase environmental quality with conservation plantings. For example, the Conservation Reserve Program (CRP), administered by the Natural Resource Conservation Service (NRCS), provides assistance to farmers and ranchers in complying with federal, state, and tribal environmental laws, and it encourages environmental enhancement. It encourages farmers to convert highly erodible cropland or other environmentally sensitive acreage to vegetative cover, such as native grass-legume mixtures and trees (Figure 13-19). Farmers receive an annual rental payment for the term of a 10–15 year contract. The CRP reduces soil erosion, protects food and fiber production resources, reduces sedimentation in streams and lakes, improves water quality, establishes wildlife habitat, and enhances wetland resources.

Nationwide, more than 36 million acres (15 million hectares) of land are enrolled in the CRP, and it is making a difference to the environment. A recent study by the University of Missouri [Food and Agricultural Policy Research Institute (FAPRI), 2007] showed that in states east of the Mississippi River, CRP lands reduced soil, nitrogen, and phosphorus runoff per acre by 6.5 tons, 21 pounds, and 1 pound, respectively (14.6 tonnes/hectare, 24 kilograms/hectare, 1.1 kilograms/hectare) compared to conventional cropping practices. In the drier western half of the United States, the CRP reduced soil, nitrogen, and phosphorus loss per acre by 13.1 tons, 22 pounds, and 6 pounds, respectively (29 tonnes/hectare,



Lynn Betts, USDA-NRCS.

FIGURE 13-18
An agricultural landscape in Caroll County, Iowa. Corn and soybeans are grown on most of the landscape. A shelterbelt of trees is planted to break the force of winds. A grass filter strip planted along a stream helps keep sediment and farm chemicals out of the stream and out of Lake Panorama farther downstream.



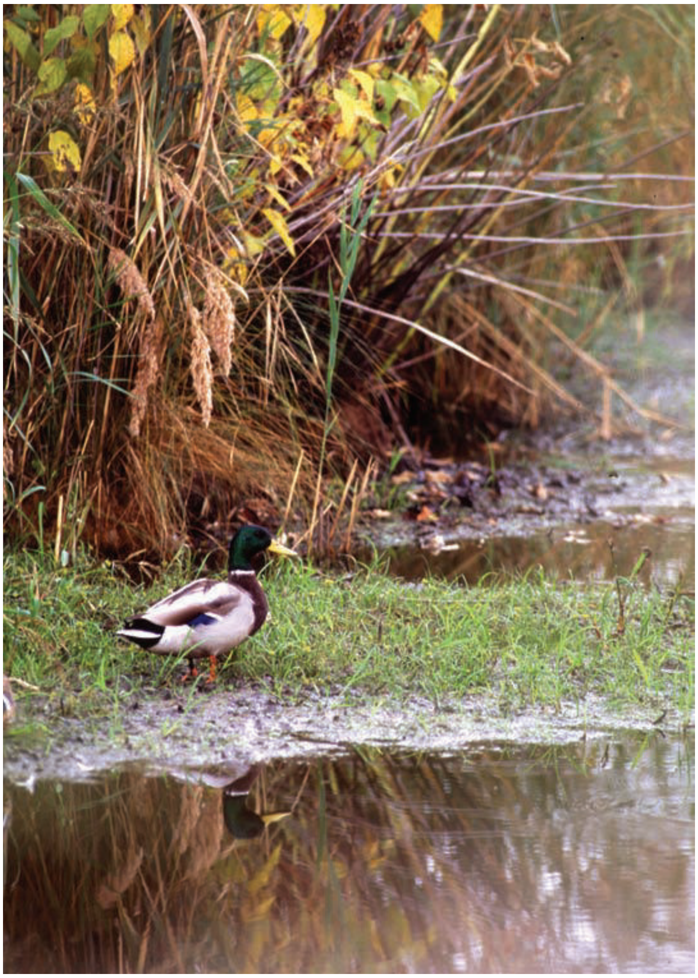
FIGURE 13-19
A conservation planting of perennial native grasses and trees in an area adjacent to a waterway. The planting reduces water and sediment flow into the waterway and also stabilizes the river bank to prevent erosion. Soybean is being grown in the adjacent field.

25 kilograms/hectare, 7 kilograms/hectare). Nationwide, the CRP increased total organic carbon in the soil by 0.7 ton/acre (1.6 tonnes/hectare) annually. An additional survey of CRP grasslands in North Dakota and South Dakota by the U.S. Fish and Wildlife Service showed that the CRP programs resulted in 1.8 million more grassland birds such as dickcissels, sparrows, and meadowlarks compared with conventional farmlands.

Riparian Buffers and Shelterbelts

Protecting natural resources from nutrient runoff, wind and water erosion, or other degradation is a key consideration in the long-term health of agricultural landscapes. Therefore, agricultural areas can benefit from two other types of plantings for conservation: riparian buffers and shelterbelts. **Riparian buffers**, or *filter strips*, are swaths of trees, shrubs, or grasses planted along the banks of streams, rivers, wetlands, or lakes (Figure 13-20). The plantings protect the banks from erosion and act as a catch for soil, nutrients, and agricultural chemicals, preventing them from entering waterways. Government programs and conservation organizations can often offset or mitigate the costs of installing and maintaining buffer strips. In addition, riparian buffers provide habitat for wildlife, as well as enhance the aesthetic quality of agricultural landscapes.

Shelterbelts or windbreaks were widely implemented in the United States following the severe soil erosion that occurred after the Dust Bowl of the 1930s. **Shelterbelts** are rows of trees at the ends of fields that slow wind velocity and protect crops and buildings from wind erosion and wind damage (Figure 13-21). Water erosion is reduced, snow cover is enhanced in cold climates, and a habitat for beneficial predators and other wildlife is provided by the shelterbelt. Grazing livestock are also protected from wind in areas with severe winters. To maximize the protective quality of shelterbelts, evergreen and deciduous trees can be planted together. Like a riparian buffer, shelterbelts also add aesthetic value to agricultural landscapes.



Scott Bauer, USDA-ARS.

FIGURE 13-20
Wetland and streamside vegetation serves as a buffer to filter excess nutrients from agricultural land and provides habitat for wildlife.



Erwin C. Cole, USDA-NRCS.

FIGURE 13-21
Windbreaks in North Dakota protect the soil against wind erosion.

Review Questions

1. Use an example to describe the differences between continuous cropping and crop rotations.
2. What are some advantages of crop rotations compared to continuous cropping?
3. How are perennial legumes such as alfalfa effective in crop rotations?
4. What are polycultures, and what advantages do they have compared to monocultures?
5. Describe the differences between mixed intercropping and strip cropping.
6. What are living mulch systems?
7. What is multiple cropping, and what is its advantage?
8. What are some advantages of using cover crops?
9. What is the purpose of green manure, and which crops are commonly used to produce green manure?
10. Discuss the Conservation Reserve Program and its purpose.
11. What is the difference between a shelterbelt and a riparian buffer?

Critical Thinking

1. Why should citizens care about the cropping systems used for production of their food?
2. Are government-supported programs such as the CRP a good investment? Does your state have any additional land preservation programs that achieve the same goals?
3. What federal agencies are charged with stewardship of land resources?
4. What are the justifications for using monocropping and continuous cropping systems for a crop such as corn?

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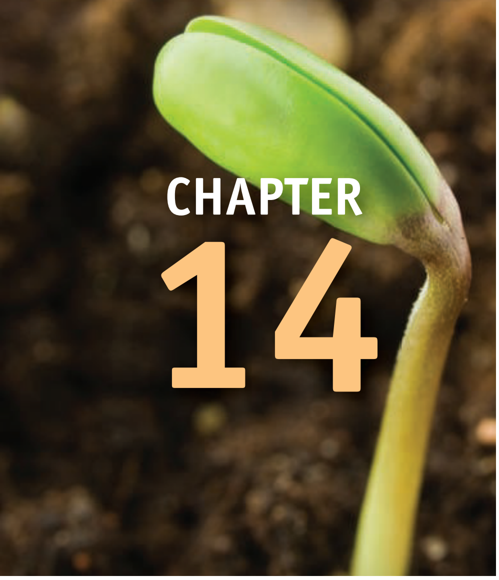
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CHAPTER 14



Tillage and Crop Establishment





Key Concepts

- Establishing crops is a multistep process that begins with preparing the land for planting through tillage.
- Conventional and conservation tillage are the two main tillage approaches. Conventional tillage usually leaves less than 15 percent residue on the soil surface, whereas conservation tillage leaves 30 percent or more residue on the soil surface.
- Tillage can incorporate residues as well as fertilizers, manures, and lime. Tilling can control crop pests and provide a seedbed to accommodate seeding equipment.
- Most crops are grown from seed bought from private, commercial companies that own the genetic traits of the seed.
- Federal seed laws require commercial seed labels to inform the farmer and consumer about the seed's characteristics.
- The seed certification process insures the genetic uniqueness and quality of a seed and allows for orderly production of high-quality seed for consumers.
- For successful crop establishment, planting depth, seeding rates, and seeding dates need to be optimized.
- Crops are established by either broadcasting or drilling the seed.

Key Terms

broadcasting
chisel plow
conservation tillage
disk
drilling
federal seed laws
grain drill
harrow
moldboard plow
mulch tillage
no-till
no-till grassland drill
planting date
planting depth
pure live seed (PLS)
ridge tillage
row crop planter
seed certification
seeding rate
strip tillage
tillage

Introduction

Crop production is a multistep process that begins with crop establishment. Before planting, the land must be prepared with tillage. The earliest farmers often had to drastically alter the vegetation on the land to plant a crop. Today, farmers usually contend only with residue from the previous crop. Successful establishment depends on use of viable seed as well as equipment that incorporates the seed to the proper depth.

Tillage

Tillage has historically been a critical step in land preparation before planting of crops. However, tillage approaches have changed over time, especially with the greater emphasis today on soil conservation, the development of improved planting equipment, and chemicals for pest control. The range of tillage approaches varies from moldboard plowing to no-till. Producers' goals influence their choice of tillage methods, and these goals may include the following:

1. Incorporation of residues. Herbage and roots from native vegetation and previous crops are incorporated into the soil to increase their rate of decay. When perennial crop fields are converted to annual crops, tillage buries the plant residue.
2. Control of crop pests such as diseases, insects, and weeds. Diseases and insects that live or survive in crop residues can often be destroyed when the residue is incorporated. Tillage can also be used to control annual and perennial weeds prior to planting.
3. Incorporation of manures, fertilizers, and lime into the root zone of the plant
4. Preparation of a seedbed to accommodate seeding equipment
5. Alteration of physical conditions and temperature of the soil. Tillage can reduce soil compaction by mixing soils, and increase soil temperatures and help dry soils in the spring.

Conventional Tillage

Conventional tillage, also called *traditional tillage*, is at least a two-step process that involves a primary tillage that uses plows to disrupt and turn the soil, followed by secondary tillage that smoothes the soil surface. Conventional tillage is used on about 100 million acres (40.5 million hectares) across all crops in the United States (Table 14-1).

The **moldboard plow** is an important primary tillage tool used by farmers (Figure 14-1). Some primitive versions of the moldboard plow date back to Roman times. Moldboard plows with iron and steel plowshares were responsible for the westward expansion of agriculture in the United States. Moldboard plowing was essential for breaking the soils of the grass prairies on the Great Plains. It creates significant soil disturbance by shearing off a section of the grass sod and flipping

TABLE 14-1

Conservation and other tillage types by millions of hectares and percentage of all planted area for the United States in 2004. Reduced-till is a hybrid system that leaves 15–30% cover. *USDA-ERS (2006)*.

	Millions of acres	Millions of hectares	% of planted area
Conservation tillage: more than 30% residue cover after planting			
No-till	62.5	25.3	22.6
Ridge-till	2.2	0.9	0.8
Mulch-till	47.9	19.4	17.4
Reduced-till: 15–30% residue cover after planting	59.6	24.1	21.5
Conventional-till: 0–15% residue cover after planting	104.5	42.3	37.7

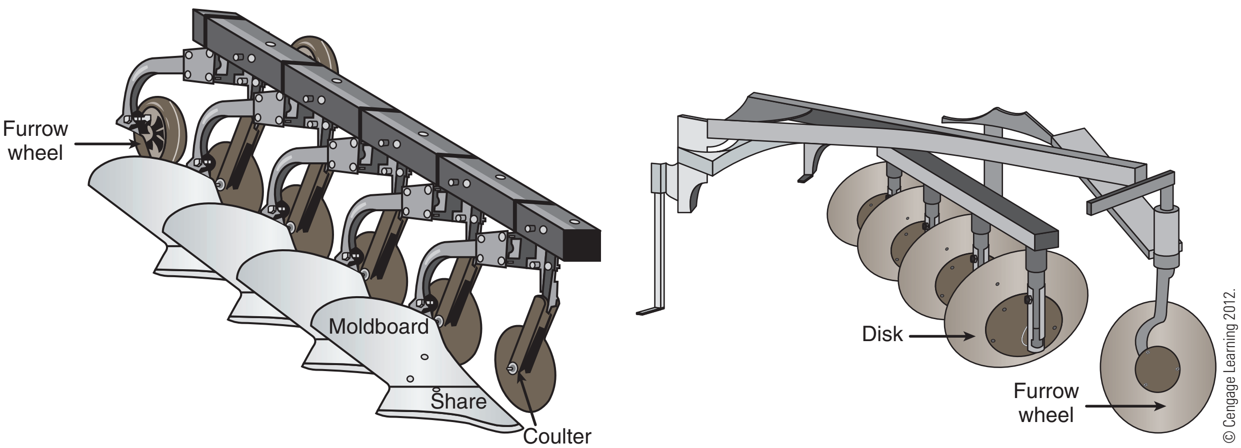


FIGURE 14-1 The moldboard (left) and disk plow (right) are primary tillage implements that are effective at burying crop residue. Use of both tillage implements is being replaced by use of the chisel plow, which leaves more residue on the soil surface and requires less energy.

it over (Figure 14-2). Usually, moldboard plowing cultivates the soil to a 6-inch (15.2-centimeter) depth, but on some soils, larger plows can be used to mix soils to greater depths. Moldboard plowing incorporates most of the crop residue that was left on the soil surface, but it also leaves the soil surface vulnerable to erosion. Residue is measured as the percentage of the actual soil surface that is covered with remains of the previous crop (Figure 14-3). Typically, in moldboard plowing,



FIGURE 14-2 A moldboard plow is used to bury crop residue.

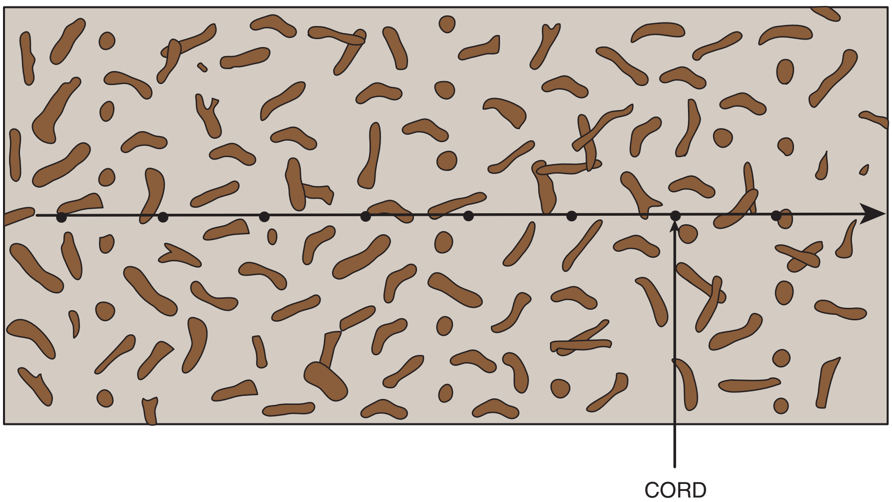


FIGURE 14-3 Calculating percentage residue cover. A 50-foot cord with marks every 6 inches is extended across the rows in the field. The total number of residue pieces touched by each mark is the percentage coverage.



FIGURE 14-4
A disk can be used as primary or secondary tillage equipment depending on the size and crop residue present. Here, a disc is being used for primary tillage in a corn field.

John Deere.

less than 15 percent of the previous crop residue remains. Excessive plowing can lead to the loss of soil organic matter. Modern moldboard plows are typically pulled in gangs of three or more (Figure 14-2).

Secondary tillage is usually done by **harrows**. Harrowing smoothes and levels the field and reduces soil particle size. Several types of equipment including field cultivators, spring tooth harrows, and disks can be used for harrowing (Figures 14-4 and 14-5). **Disks** are common, secondary tillage equipment and, if large enough, can also be used for primary tillage. A disk is a large, concave plate with a sharp edge for slicing and mixing the soil. Most disks incorporate materials from 3 to 6 inches (8 to 15 centimeters) into the soil.

Conservation Tillage

Conservation tillage is an approach that can create variable levels of soil disturbance, but by definition, leaves 30 percent or more of the crop residue on the soil surface. Conservation tillage is used on about 40 percent of the crop acres in the United States. Mulch tillage, ridge-till, and no-till are three conservation tillage approaches. The conservation tillage approach is possible because of developments in equipment that can plant seed directly into residues, and the development of



FIGURE 14-5
A field cultivator being used as a harrow for final preparation of the field before planting.

John Deere.

herbicides for post-emergence control of weeds (see Chapter 15). Conservation tillage is an important practice for reducing soil and water erosion. Crop residues protect the soil from the impact of rainfall. They enhance soil organic matter levels and water infiltration, and they decrease soil and nutrient movement. Crop residues decrease moisture loss from the soil surface. Conservation tillage also requires less time and energy than conventional tillage.

Crops vary greatly in residue contribution. When harvested for grain, there are from 3–5 tons/acre (7–11 tonnes/hectare) of corn stover (stalk, leaves, cobs, and husks) remaining. Soybean (1 ton/acre; 2.2 tonnes/hectare) and small grains (2 tons straw/acre; 2.5 tonnes/hectare) contribute fewer residues.

Mulch Tillage

Mulch tillage is a tillage system that involves one to three tillage operations. The **chisel plow** is a primary conservation tillage implement used in mulch tillage. It consists of a small blade or tool attached to a shank (Figure 14-6). The blades attached to the shanks can vary depending on the soil type and goal of the producer. In contrast to the moldboard plow, the chisel plow does not turn the soil over, and it provides minimal incorporation of residues (Figures 14-7 and 14-8). Typically, chisel plows penetrate to a 10-inch (25-centimeter) soil depth. Following chisel plowing, secondary tillage with a disk is often used.

No-Till

No-till is an approach that does not use primary tillage in which specialized planters with disk openers slice through crop residues and precisely deposit the seed at a desired depth (Figure 14-9.) The seed is covered, and the soil is firmed around the seed. No-till, which involves minimal crop residue disturbance, also minimizes soil erosion and maximizes soil organic matter and soil water conservation. No-till approaches are used less in northern latitudes because surface residues insulate the soil, causing it to warm up too slowly in the spring and thus delaying planting.



FIGURE 14-6
Chisel plows are enlarged field cultivars that have shanks to which various tools or blades can be attached.

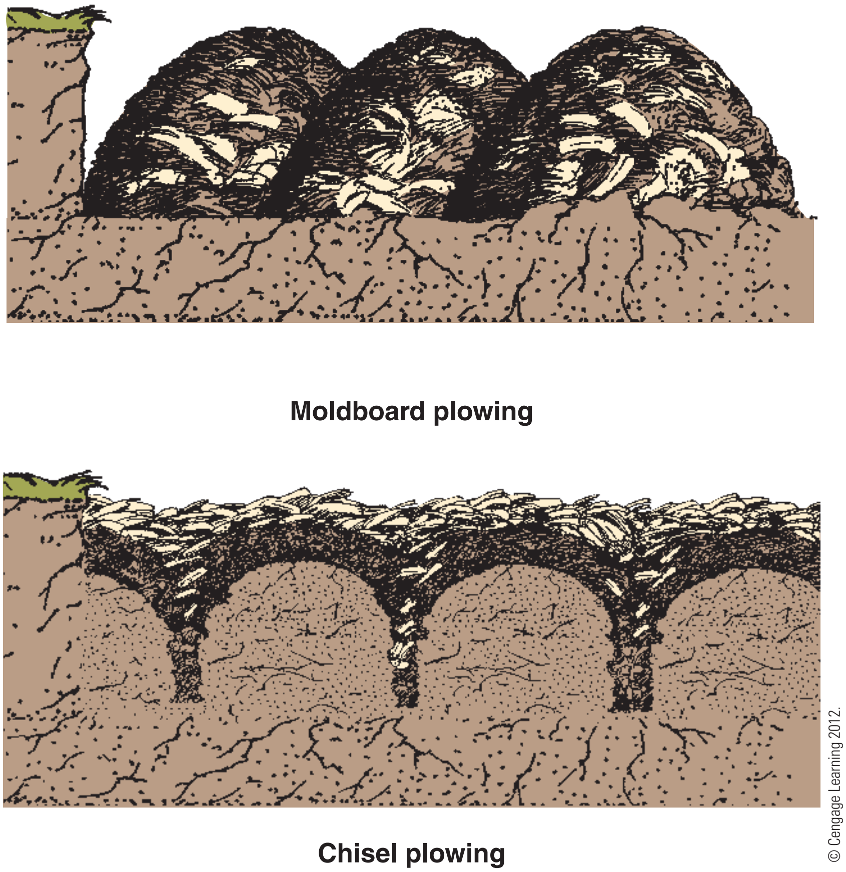
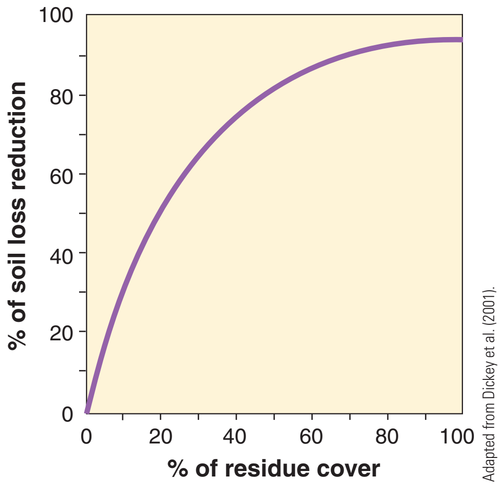


FIGURE 14-7
The impact of tillage systems on the soil. Moldboard plowing, a conventional tillage, is the approach that incorporates the most crop residue. Chisel plowing, a conservation tillage practice, leaves more residue on the soil surface. It is becoming the most popular tillage process.

FIGURE 14-8 Crop residue decreases soil erosion by protecting the soil surface from rainfall impact and increasing water infiltration. Conservation tillage is a tillage and planting system that leaves at least 30 percent of the soil surface covered by residue after planting.



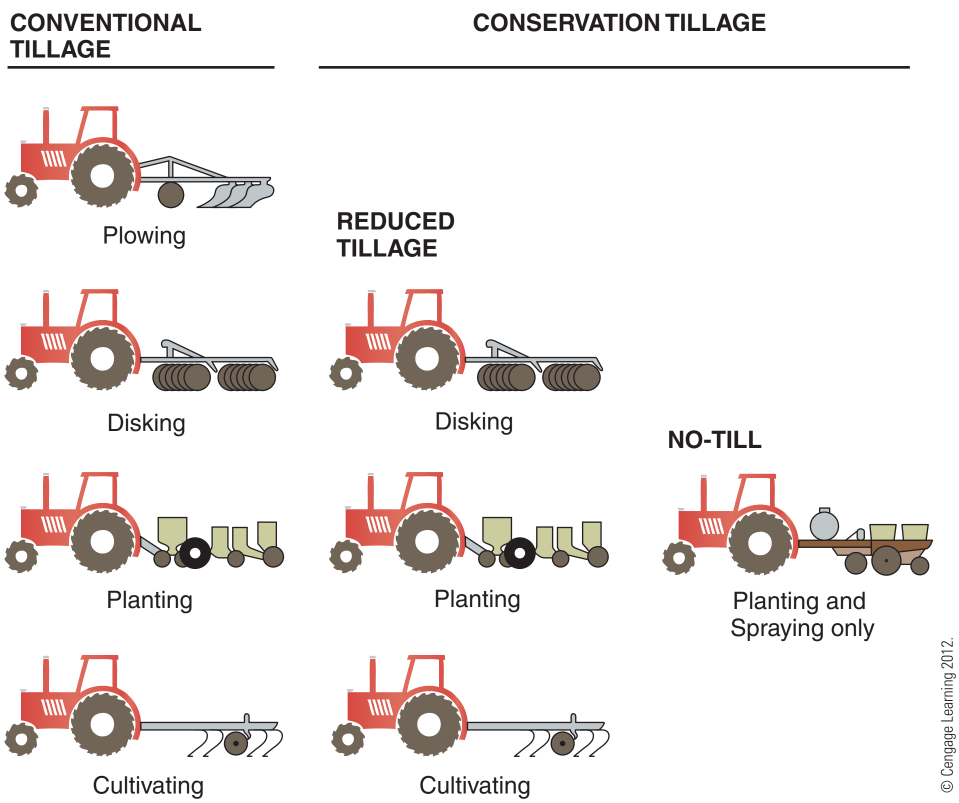


FIGURE 14-9 There is a range of approaches to preparing a seedbed and planting a crop. Conventional tillage that uses a moldboard plow is the most traditional and causes the maximum soil disturbance. In contrast, no-till approaches have a minimum disturbance of the soil, specialized planting equipment, and only herbicides for weed control.

Ridge Tillage

Ridge tillage of row crops, such as corn and soybeans, involves specialized tillage and planting equipment. In ridge tillage, ridges of soil about 6 inches (15 centimeters) high are created during the final cultivation of a row crop and, in the subsequent year, the following crop is planted directly into the ridge (Figure 14-10). The ridges are maintained in succeeding years through cultivation. In the spring, the ridges become warmer and dry faster than the surrounding soils. Ridge tillage is very effective in reducing water movement and soil loss.

Strip Tillage

Strip tillage is a conservation tillage option to no-till seeding. Special equipment creates a tilled, narrow seedbed for row crop planting, but leaves similar between-row residue as a no-till system (Figure 14-11). Strip tillage involves tilling a narrow 8- to 12-inch (20- to 31-cm) band in crop residue in the fall and planting the row crop the following spring. Sometimes fertilizers are incorporated into the tilled

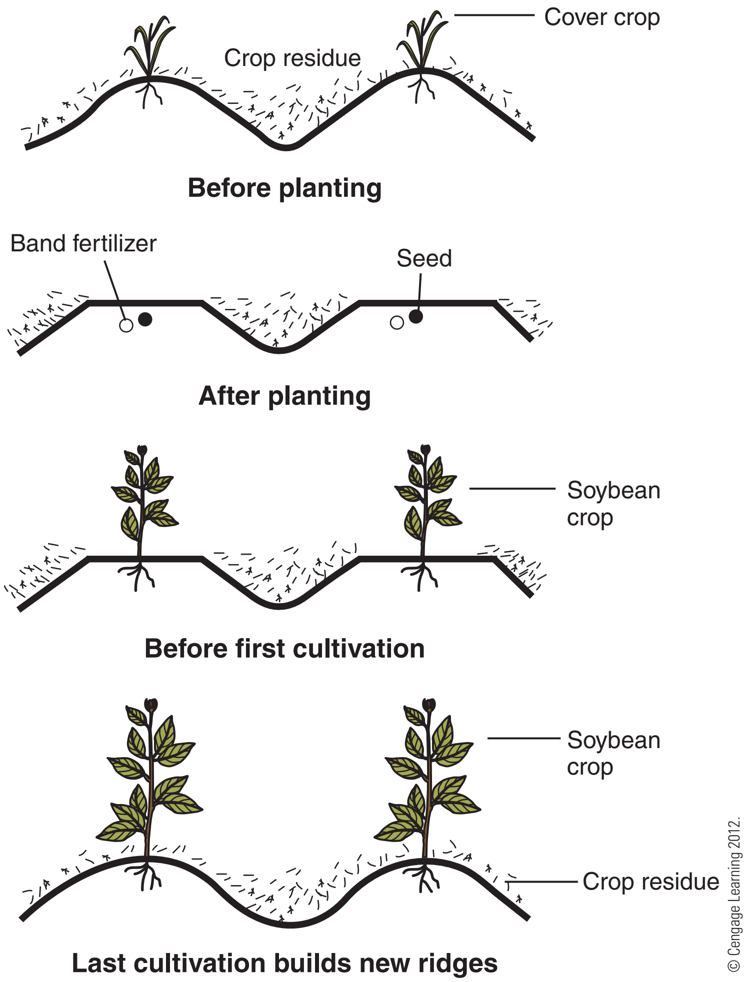


FIGURE 14-10 Ridge tillage is a conservation tillage practice that uses specialized equipment to create ridges in a field. These same ridges are then used as a raised seedbed for planting of a subsequent crop.



FIGURE 14-11 Strip till equipment (above) has coulters and other tools that remove residue and prepare seedbed (below) in a band into which the following crop is planted.

row in the fall. Strip tillage provides between-row residue cover and soil conservation like no-till, but with a warmer, spring seedbed similar to total field tillage with a chisel plow (Table 14-2). Strip tillage has comparable yields as chisel plowing but requires less energy and time inputs than chisel plowing (Table 14-3). In northern regions with colder soils, strip tillage often does not work well with corn systems because the heavy residue can reduce soil temperatures.

TABLE 14-2

Percent soybean residue on soil surface after corn planting. *Adapted from Sundermeier and Reeder (2007).*

	In corn row	Between corn row
Moldboard plow	1%	1%
Chisel plow	30%	40%
Strip till	28%	95%
No-till	90%	95%

TABLE 14-3

Average corn yields in chisel, strip-till, and no-till systems under two rotations in Wisconsin. *Adapted from Wolkowski et al. (2009).*

	Chisel	Strip-till	No-till
Continuous corn rotation	180	165	160
Soybean-corn rotation	190	190	175

Timing of Plowing

Farmers plow their soil in the fall following crop removal or in the spring before planting. Fall plowing is advantageous because it allows for breakdown of crop residues during the winter and faster warm-up of the soil in the spring. Fall plowing also facilitates earlier spring planting because in the following spring, only secondary surface tillage is required prior to planting. Spring plowing leaves more crop stubble on the soil surface in the field during the winter, which will reduce wind and water erosion. On some wetter soils, timely spring plowing is not possible without delaying crop planting.

Establishing the Crop

Most crops are established from seed. In the early days of agriculture, harvested seed was saved and replanted the following year. During this process, crop improvement occurred because agriculturalists selected for specific crop traits such as seed size, color, and time of maturity. Today, some farmers still save their own seed and replant it, but for most of the important crops grown on large acreage, farmers annually purchase seed from private, commercial companies. These companies employ plant breeders and seed production specialists to develop and provide high-quality seed of varieties adapted to specific environments. Most private companies and plant breeders legally protect the genetic traits of their modern

varieties and, in these situations, it is illegal for growers to save and plant or market the seed they grow.

Federal Seed Laws

Federal seed laws have established that farmers and consumers have a right to know essential information about the seed they purchase. Marketed seed must be labeled and contain specific information (Table 14-4).

Seed Certification

During development of modern plant breeding and the commercial seed industry, a **seed certification** process was established. This process insures the genetic uniqueness and quality of a seed and allows for the orderly production of seed for consumers. The certification process is regulated by State Crop Improvement Associations. Growers who buy "certified seed" are assured that they are purchasing a high-quality seed.

Calculation of Pure Live Seeding Rate

To precisely define the quantity of seed needed to establish a crop, the percentage of **pure live seed (PLS)** in a container of seed must be determined. PLS refers to the viability of the seed and its lack of weed seeds and inert matter. The percentage of pure live seed can be determined from information provided on the seed tag. See Table 14-5 for how to calculate this.

TABLE 14-4

Essential information for the commercial seed tag.

Information	Description
Crop type and variety	Identifies the plant species and its variety name
Lot	A specific quantity of seed that is produced in a specific location and that has a uniform level of quality
Pure seed	% (weight basis) of the crop's seed that is of the designated species and variety
Other crop seed	% (weight basis) of contaminating other crop seed
Weed seed	% (weight basis) of weed seed (commercial seed cannot contain noxious weed seed)
Inert matter	% (weight basis) of nonliving material such as soil, rocks, and cracked seed
Germination	% of the total seed that germinates to produce normal seedlings
Date of test	Year and month that the seed test was conducted (old test results may not be reliable)
Origin	Production site for the seed
Name/address	Name of the seed company or seed vendor and their location

TABLE 14-5

Calculation of the percentage of pure live seed and seeding rates.

% PLS = 100 × [(% germination) × (% purity)]

Example:

1. Given on the seed tag:

% germination	92% (0.92)
% inert matter	1.5%
% other crop seed	0.6%
% weed seed	0.1%

2. Calculate % purity (pure seed):

100%	pure seed
−1.5%	inert matter
−0.6%	other crop seed
−0.1%	weed seed
97.8% (0.978)	pure seed in this seed lot

3. Calculate % pure live seed (%PLS):

% PLS = 100 × [(% germination) × (% purity)]
= 100 × [(0.92) × (0.978)]
= 100 × 0.90
= 90.0%

Once you have determined the % PLS, you can use this information to determine the amount of seed necessary to seed a crop at the recommended rate.

Example:

1. Given information:

   55 pounds/acre = seeding rate of soybeans/acre

   90% (0.90) = % PLS

2. Calculate pounds of this seed lot required:

   a. Seed required × 0.90 = 55 pounds/acre

   b. Seed required = 55 pounds/acre ÷ 0.90 = 61.1 pounds/acre of seed from this seed lot

Successful Seeding

In natural systems, plant seeds are deposited on the soil surface and penetrate the soil by the action of precipitation, freezing and thawing, or rodents. This is an effective reproductive strategy for plants that produce a large number of small seeds, but often will not be profitable in modern crop production systems. In modern systems, seed is expensive, and specific planting strategies are required for profitable crop production.

Depth of Planting

Planting depth in the soil is a critical factor in successful crop establishment. Seed that is planted too deep will exhaust its energy reserves before it reaches the soil surface and will be unable to make new energy through photosynthesis. In contrast, seed planted on the soil surface or very shallowly may initially absorb water but then dry out and die because the roots are not able to reach soil moisture. Crop seed is planted at a prescribed depth to insure stand establishment and uniform plant emergence (Tables 14-6 and 14-7). Determining the correct seeding depth depends on the following factors:

- **Seed size.** A general rule of thumb for the depth is no deeper than 10 times the diameter of the seed. Large seeds generally have more vigor than small seeds because of their greater energy reserves. Small-seeded crops such as

TABLE 14-6

Seeding depth and seed size.

Depth of seeding		Seed size		
inches	cm	no./pound	no./kilogram	Representative crops
0.25–0.50	0.6–1.3	60,000–1,000,000	135,000–2,250,000	Redtop, timothy, bluegrass, fescue, white clover, alsike clover, and tobacco
0.50–0.75	1.3–1.9	30,000–60,000	67,500–135,000	Alfalfa, red clover, sweet clover, crimson clover, ryegrass, foxtail millet, and turnip
0.75–1.50	1.9–3.8	10,000–30,000	22,500–67,500	Flax, Sudan grass, proso, and bromegrass
1.50–2.00	3.8–5.1	2000–10,000	4500–22,500	Wheat, oats, barley, rye, rice, sorghum, buckwheat, vetch, and mung bean
2.00–3.00	5.1–7.6	80–2000	180–4500	Corn, pea, cotton, and soybean

TABLE 14-7

Plant populations produced from 100 seeds at various depths on two soils. 1 inch = 2.54 cm. *Adapted from Sund et al. (1966).*

	Number of plants in sand				Number of plants in clay			
	Depth (inches)							
	½	1	1½	2	½	1	1½	2
Alfalfa	71.4	72.6	54.8	40.1	51.9	48.4	28.1	13.1
Red clover	67.3	65.9	53.1	27.1	40.1	35.1	14.2	7.2
Bromegrass	70.5	64.2	48.0	29.1	56.1	37.4	17.2	5.5
Orchard grass	61.2	56.4	30.1	12.6	60.1	25.9	6.3	1.2



Scott Bauer, USDA-ARS.

FIGURE 14-12 Planting of foxtail millet using a grain drill. For small-seeded crops, establishment is improved using specialized equipment with depth-control capability.

alfalfa and orchard grass are especially vulnerable to seedling mortality if planted too deep (Figure 14-12).

- **Seedling morphology.** A seed's morphological characteristics and type of emergence affect planting depth. Seeds with epigeal emergence such as soybeans, where the cotyledons emerge aboveground, can be more hindered by crusting of the soil surface than seeds of plants such as grasses that have hypogeal emergence. Also, corn has a unique ability to emerge from deeper soil depths than other crops because it has a specialized stem structure (the mesocotyl) that, combined with the coleoptile, pushes the seedling above the soil surface.
- **Soil moisture.** Within the recommended planting range, seeds are planted as deep as possible to maximize contact with soil moisture.

- **Soil texture.** Soil texture influences seeding depth. In sandy soils, crops are sown deeper than in clay soils. A sandy soil has lower moisture-holding capacity and more pore space than clay soils and is less subject to crusting following rain.

Environmental Factors Affecting Seed Germination

For germination of viable seeds to occur, certain environmental conditions must be met. Moisture, temperature, oxygen, and sometimes light are important factors. In addition, seeds often have dormancy.

Moisture

Before planting, most seeds contain less than 15 percent moisture. For germination to occur, seeds need to absorb a significant amount of their weight in moisture. Most seeds will not initiate germination until a critical level of seed moisture is reached. Sugar beet seed requires absorption of nearly 100 percent of their dry weight; soybean and corn typically absorb 75 percent and 40 percent of their dry weight, respectively. Once the germination process is initiated and the seed coat is broken, deprivation of water often causes the germinating seed to die. This explains why surface sowing of seed without incorporation often results in failure. Seed can germinate when rainfall occurs, but because the roots have not penetrated the soil, they will be unable to obtain enough water to sustain the new plant.

In contrast, drilling the seed into soil increases the chances that the root will grow down into soil moisture and protect the seed from drying out. Use of moderate pressure supplied by press wheels is a practice that also increases moisture availability to the seed by increasing soil-seed contact.

Temperature

Temperature affects the rate of metabolic reactions within a plant. Plants originating in tropical or subtropical regions—for example, soybean, corn, and rice—have a higher minimum, optimum, and maximum temperature for germination than plants such as wheat, alfalfa, and flax that originated in temperate regions. Minimum temperatures for germination of cool-season, temperate species range from 40–50°F (4–10°C). For warm-season, tropical species, minimum temperatures range from 50–60°F (10–16°C).

Oxygen

Many plant metabolic processes such as respiration require oxygen. Air diffuses into the soil, and therefore oxygen is usually not a limiting factor. However, if soils are flooded or compacted, anaerobic conditions can lead to seed death. Wild and cultivated rice are exceptional species in that their seeds can germinate under anaerobic underwater conditions.

Light

Many species can germinate in either light or darkness. However, certain small-seeded species such as lettuce and Kentucky bluegrass that germinate near the soil surface require light for germination.

Dormancy

Some seeds undergo a period of dormancy before germination. Dormancy is the failure of a seed to germinate when all required environmental conditions are met. Some level of seed dormancy is desirable to prevent seed germination while the seed is mature and still on the plant, but is an undesirable trait for seed destined for planting. Seed dormancy is a natural mechanism that extends the germination time of a species—sometimes over years—and ensures that some plants will become established under favorable growing conditions. Seed dormancy is induced by physical barriers, internal, chemical, and physiological factors called *after-ripening*.

The seed coat is a physical barrier to seed germination. Seeds of many legumes such as alfalfa and clovers contain specialized layers in the seed coat that make them impervious to water and air. This seed will not germinate and is called *hard seed*. These seed coatings must be abraded or scarified (scratched) to enable germination. In a soil environment, fungi or insects can disrupt these seed coats. For commercial purposes, seeds are scarified by mechanical or chemical means to disrupt the seed coat before sale.

Other plant seeds can contain chemical compounds that inhibit their germination. These chemical compounds must be leached from the seed prior to germination. Chemical inhibitors have been found in sugar beet, oat, rice, and barley.

Though seed of corn can germinate soon after maturity, seed of some cereal varieties of wheat, barley, and oat undergo a dormancy period for several months. This is called *after-ripening* and involves further development of the seed embryo.

The Germination Process

Germination occurs in several stages as the seed changes from a resting state to active growth.

- The first step in the germination of a seed is the absorption of water by the seed through the seed coat. The water then diffuses throughout the seed.
- The second stage is the initiation of metabolic processes within the seed. These include the activation of enzymes for the breakdown of stored foods into simpler compounds (e.g., starch to glucose; proteins to amino acids; oils to fatty acids), the development of respiration, and cell division within the embryo.
- The third stage is the growth of the embryo, the living plant. Initially, the radicle (the root) emerges from the seed, followed by the shoot.

Seeding Rates

For economic production of most crops, agronomists have identified optimal **seeding rates** that are specific for climatic regions (Table 14-8). These are based on an assumption of a certain level of seedling mortality. The general response of an annual crop yield to increasing populations is shown in Figure 14-13. At low seeding rates, plant populations are inadequate to use all the light, moisture, and nutrient resources. As population increases, a point is reached when the population is optimum to use all resources. After this point, there is diminishing response to increased populations. Agriculture research continually evaluates the optimum seeding rates for crops (Table 14-9).

TABLE 14-8

Recommended planting rates for a diversity of crops in Minnesota. *Adapted from University of Minnesota Agricultural Experiment Station (2010).*

Crop	Pounds/ acre	Kilograms/ hectare	No. of seeds/acre	No. of seeds/hectare
Barley	85	95	1,219,700	3,012,600
Corn	17	19	33,000	81,500
Kidney	115	129	105,000	259,400
Navy	42	47	105,000	259,400
Flax	42	47	3,702,600	9,145,400
Bromegrass	16	18	2,178,000	5,379,700
Alfalfa	13	15	2,860,000	7,064,000
Red clover	9	10	2,178,000	5,379,700
Oat	80	90	1,219,700	3,012,600
Rye	60	67	1,089,000	2,689,800
Sorghum	10	11	150,000	370,500
Soybean	56	63	140,000	345,800
Sunflower, nonoilseed	4	4	17,000	42,000
Sunflower, oilseed	3	3	23,000	56,800
Wheat, durum	90	101	1,089,000	2,689,800
Wheat, hard red spring	113	127	1,582,000	3,916,400
Wheat, winter	75	84	1,089,000	2,689,800
Buckwheat	50	56	740,500	1,829,100
Canola	8	9	1,089,000	2,689,800
Fieldpea	180	202	392,000	968,300
Foxtail millet	15	17	3,267,000	8,069,500
Proso millet	20	22	1,306,800	3,227,800
Wild rice	33	37	261,400	645,600

Seed Treatment

Seed of many crops are treated before they are packaged for purchase. The most common seed coatings are used to control soil fungi and insects that attack the seed before and during germination. For example, corn and soybean seeds are treated with fungicides to control soil fungi such as *Pythium*, *Phytophthora*, *Rhizoctonia*, and *Fusarium* that may damage the seed before and during germination. Insecticides applied to corn seed can provide protection against insects such as wire worm, corn root worm, and seed corn maggot. In addition, the seeds of

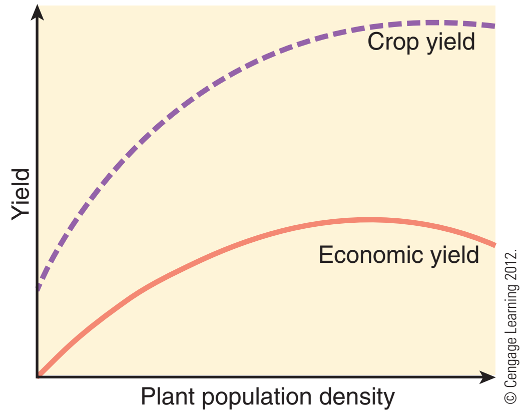


FIGURE 14-13
Relationship between plant population density and yield.

TABLE 14-9

Relationship between corn plant population and grain yield for corn planted prior to May 1. *Adapted from Hicks et al. (1999).*

Plant population (plants/acre)	Plant population (plants/hectare)	Grain yield population (%)
30,000	74,132	100
28,000	69,190	98
26,000	64,247	94
24,000	59,305	92
22,000	54,363	88
20,000	49,421	84
18,000	44,479	79

legumes, such as soybeans and alfalfa, are treated with a specific *Rhizobium* species (bacteria) that nodulates the roots of the legumes. Nodulation is the first step in the biological nitrogen-fixation process (see Chapter 8).

Seeding Equipment

Broadcasting and drilling are two approaches to seeding crops. **Broadcasting** consists of even spreading of seed on top of the seedbed across a field, but not in rows (Figure 14-14). Manual broadcasting of seeds was used for centuries to sow seeds, but the practice has been replaced by mechanization. Broadcasting is now routinely used for sowing small-seeded forage legumes and grasses such as alfalfa and smooth bromegrass. Examples of broadcast equipment include the cultipacker seeder that drops seed from a hopper and then covers the seed with corrugated



Brillion Iron Works, Inc.–Farm Equipment Division.



University of Minnesota, Craig Sheaffer.

FIGURE 14-14 Broadcast seeder for establishing alfalfa and other small-seeded legumes and grasses. The seedbed that is formed after using this seeder to broadcast seed (below).

rollers, and air seeders that disperse seed on the soil surface (Figure 14-15). With surface broadcasting on prepared seedbeds, it is important to follow the seeding with soil-packing equipment to insure seed coverage. Some farmers practice frost seeding during winter months. Frost seeding is the broadcast seeding of desirable forage grasses and legumes while the ground is frozen. The seed is then covered as the soil freezes and thaws.

Drilling consists of depositing seed in a row at a uniform depth in a seedbed. Drills provide for greater seeding precision than broadcast seeding. Most drills have hoppers for carrying seed and fertilizers, a metering device for

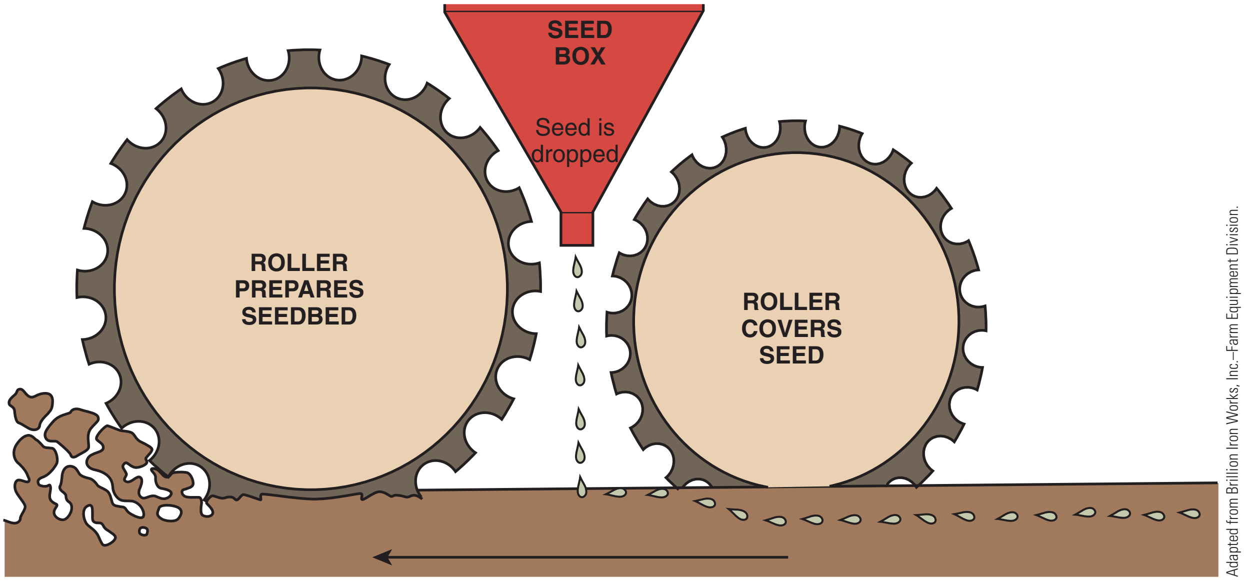
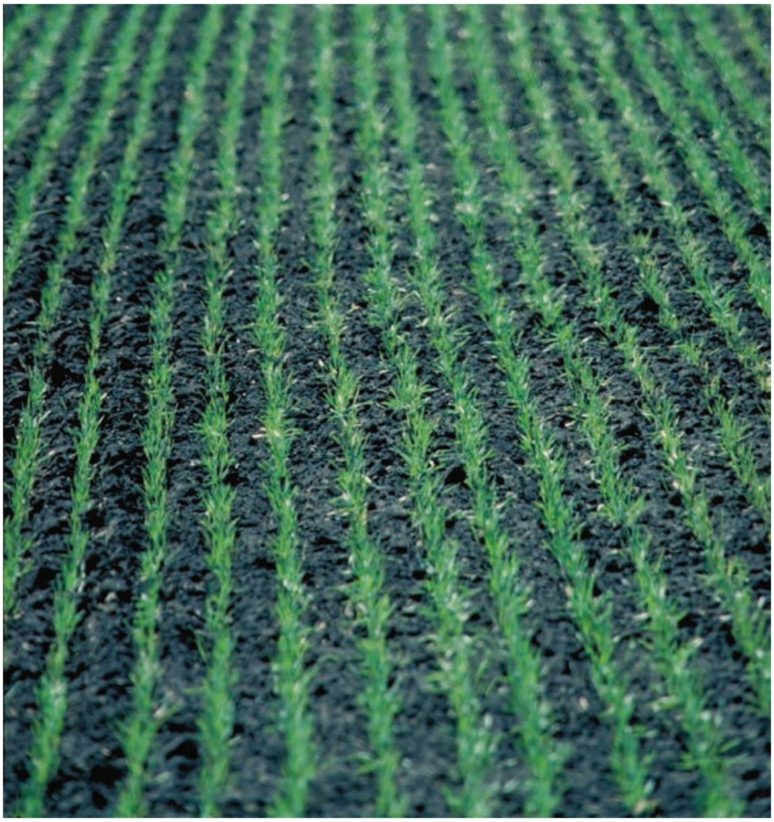


FIGURE 14-15 Broadcast seeding. The front roller forms a firm seedbed, the seed is metered out, and the back roller firms the soil over the seeds.

a specific-sized seed, and openers (the drills) for placing the seed into the soil. Many drills are equipped with instruments to control the planting depth and press wheels to insure good soil-seed contact. There are various types of drills.

- **Grain drills.** These drills plant grains in narrow rows that are often only 6 inches (15.2 centimeters) apart (Figure 14-16). This is the most traditional approach for seeding crops like wheat, barley, and oats, but drills are now also used for soybeans.
- **No-till grassland drills.** These drills are used to improve the species composition of grasslands and pastures. Legumes such as alfalfa and clovers are interseeded into permanent cool-season grass pastures to improve productivity and forage quality. Native perennial grasses and forbs are seeded into killed sods to restore prairies. These drills are similar to grain drills, except that they must meter very small and, sometimes, fluffy seed. Because the seedbeds are usually not prepared, no-till grassland drills are heavy and often contain specialized disk openers for slicing and throwing existing vegetation (Figure 14-17).
- **Row crop planters.** These types of drills are often used for corn and soybeans (Figure 14-18). Seed is deposited in rows that are usually 20–30 inches (51–76 centimeters) apart. Seed metering is very precise and drops seeds at specific spacing within a row. No-till variations of row crop planters are equipped with coulters and disks for removing the residues of previous crops (Figure 14-19).

Over time, corn and soybean row spacing has decreased. In the 1950s, very wide row spacing, sometimes up to 48 inches, was used to accommodate



Bruce Fritz, USDA.

FIGURE 14-16
Rows of barley that have been seeded with a grain drill. The rows are 6 inches apart.



University of Minnesota, Craig Sheaffer.

FIGURE 14-17
A grassland drill deposits seed into a groove cut into the soil by a coulter. The wheel on the back of the machine reseals the soil and provides soil-seed contact.



John Deere.

FIGURE 14-18
A row crop planter for seeding corn in 30-inch rows.



University of Minnesota, David L. Hansen.

FIGURE 14-19
Soybean planted into corn residue in a conservation tillage system. Corn residue controls soil erosion by wind and water.

TABLE 14-10

Soybean yields in 15-inch and 30-inch rows at different seeding rates in Iowa, 2004–2006. *Adapted from Pedersen (2009).*

	Seeding rate in seeds per acre			
	75,000	125,000	175,000	225,000
15-inch rows	68	71	72	72
30-inch rows	64	68	67	67

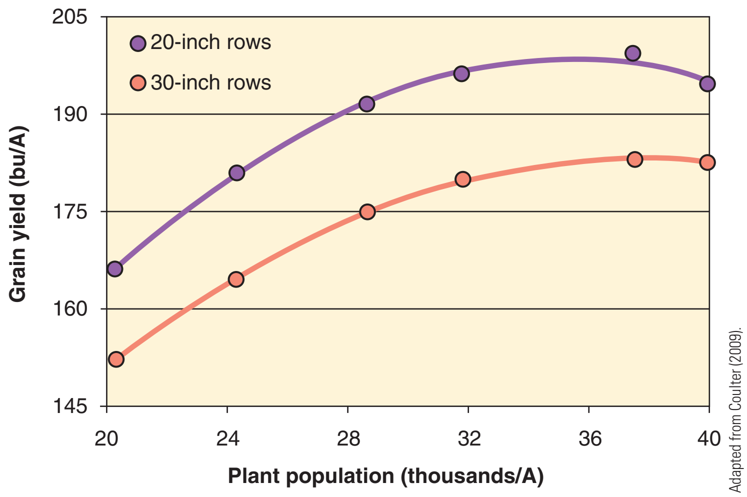


FIGURE 14-20
Corn yields for 20-inch and 30-inch rows over various plant populations in Minnesota in 2008.

tractors and cultivation for weed control. Planting corn and soybean in 30-inch rows is now commonplace, but research has shown that soybean yield can be significantly enhanced by using a 15- to 20-inch row spacing and applying herbicides for weed control. The narrower rows have a yield advantage because the plants are more equally spaced within the field and can intercept more light and use moisture better during the growing season. On average in Iowa, a 4.5 bushel per acre yield increase can be expected using 15-inch row spacing, compared to 30-inch row spacing (Table 14-10).

For corn, grain yields have not been increased consistently by decreasing row width to less than 30 inches. In some Minnesota studies, grain yields were increased by as much as 9 percent (Figure 14-20), but these responses have been inconsistent. For the entire Corn Belt, yields are increased an average of 2 percent by decreasing row width to less than 30 inches (Butzen and Paszkiewicz, 2008).

Planting Dates

Crop **planting dates** are selected to optimize crop establishment and to maximize capture of solar energy during favorable growing temperatures. Planting dates vary considerably with crops and across environmental regions of the United States. The following general guidelines apply:

- Summer-temperate, cool-season, annual plants—such as small grains—are planted as early as possible in the spring so as to take advantage of favorable environmental conditions for germination and growth. They mature during the warm summer months.
- Summer-tropical, warm-season, annual plants—such as corn, soybeans, and cotton—are planted at later dates than cool-season small grains because of their requirements for higher temperatures for germination and their frost sensitivity (Table 14-11 and Figure 14-21). In northern regions, the planting dates for corn and soybean have become progressively earlier to capture the maximum amount of solar energy during the growing season, while having the crop mature and dried for harvest in the fall. This has been possible because: with greater use of fall tillage and conservation tillage, less spring tillage is needed; corn and soybean varieties have been developed that have greater seedling vigor; and herbicides can be used for spring weed control. In addition, with increased use of soil drainage (see Chapter 10), soils in many areas are drier in the spring allowing earlier establishment.

TABLE 14-11

Yield loss by planting date for corn and soybean in Minnesota. There is an optimum date when it is best to plant. Planting too late will negatively affect yield. *Adapted from University of Minnesota Extension Service (1999) and Hicks et al. (1999).*

	Yield loss %	
Planting date	**Soybean**	**Corn**
April 25	—	0
April 30	—	1
May 1	0	—
May 5	1	3
May 10	2	6
May 15	3	9
May 20	6	12
May 25	9	14
May 30	13	17
June 4	18	23
June 9	24	29
June 14	30	35
June 19	36	41
June 24	43	—

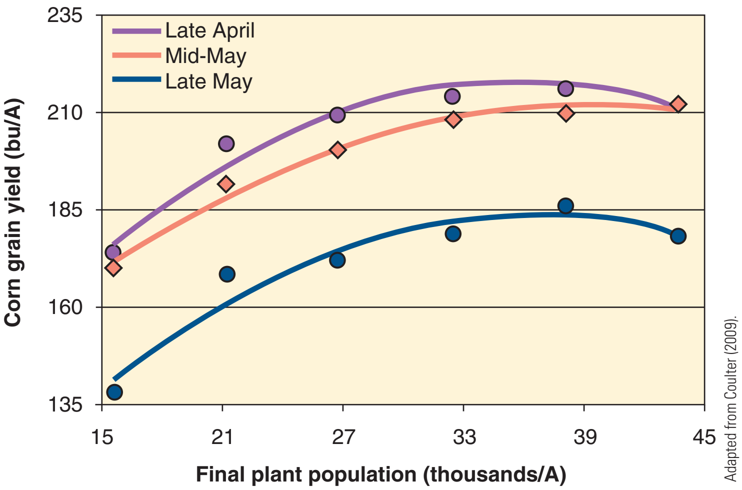


FIGURE 14-21 Research in Minnesota shows the benefit of early planting being consistent over many plant populations. The ideal plant population here is about 32,000 to 34,000 plants per acre.

- Winter-annual, temperate, cool-season crops—such as small grains, clovers, and canola—are planted in the late summer to early fall as air and soil temperatures start to decrease, and soil moisture levels are generally higher. Some winter annuals such as rye grain can tolerate low temperatures and begin growing again in the spring. Most winter annuals are grown in regions of mild winter conditions, and they have significant growth during the winter.

For all crops, planting dates are influenced by seedbed conditions, local climate conditions, and the total acres that a producer needs to plant. Planting into wet seedbeds is very risky, because it results in poor crop stands due to soil crusting, seed diseases, and poor emergence. Early planting can be risky in some climates where there are frequent late frosts (temperatures below 32°F [0°C]). Corn seedlings that have their growing points below ground can rebound from frost damage, but soybean and alfalfa seedlings that have growing points above ground can be destroyed by freezing temperatures and will need replanting. With farm size increasing, farmers may need to begin planting crops early so as to plant all their crops without suffering yield loss because of late planting.

Review Questions

1. What are the two most widely used tillage approaches, and what tillage equipment is used?
2. What are the benefits of tilling the soil?
3. What is harrowing the soil, and what equipment is typically used?
4. What is the advantage of having crop residue on the soil surface?
5. What is no-till seeding?
6. Where does most of the seed that farmers use come from?
7. Identify important information provided on the seed label.

8. What does the term *pure live seed* mean?
9. What factors must be taken into account to achieve optimal seed establishment?
10. Identify crops that are established using broadcast seeding and those that are drilled in rows.

Critical Thinking

1. Go to a home-and-garden store that sells grass seed for lawns and examine the label. What is the germination rate of the seed? Does the seed contain weed seeds?
2. Visit your local extension website. Look up the recommended seeding rates for crops grown in your area. How do they compare to those in Table 14-8?
3. Go to the Natural Resources Conservation Service website. Look up the predominant tillage practices for your area. How do they compare to the rest of the country?

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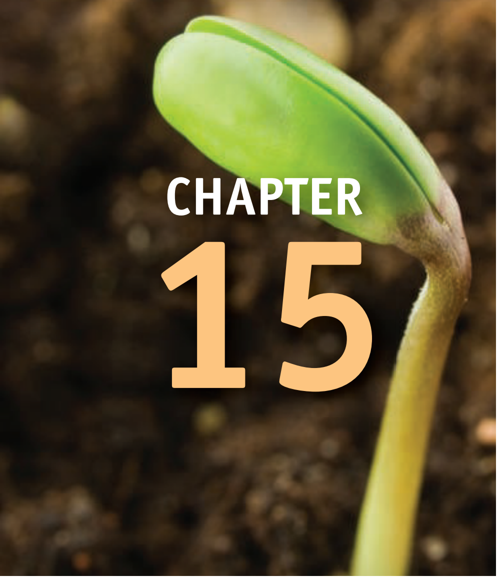
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CHAPTER

15



Weeds





Key Concepts

- Weeds are plants that reduce crop yield and the profitability of agriculture by competing with crops for moisture, light, and nutrients.
- Modern cropping systems are often annual monocultures that are vulnerable to invasion by weeds.
- Weeds are controlled using herbicides, mechanical means, and biological approaches, with herbicides being the most widely used strategy.
- Herbicide labels are an essential part of the governmental regulation process and are critical for safe use of products.
- Herbicides kill plants by using a specific mode of action. They are described based on when they are applied (preplant, preemergence, postemergence, and postharvest).
- Cultural practices for weed control include crop rotation, cover crops, and planting date.
- Biological weed control employs agents such as insects, diseases, and animals.
- Tillage is a traditional approach to weed control.
- Integrated approaches to weed control are the most sustainable for profit and the environment.

Key Terms

active ingredient
allelopathy
amino acid synthesis inhibitor
aquatic
biological weed control
biotype
broadleaf
cell membrane disruptor
contact herbicide
Environmental Protection Agency (EPA)
general use pesticide
glyphosate
growth regulator
herbicide
herbicide resistance
herbicide tolerance
inert ingredient
LC_{50}
LD_{50}
lipid synthesis inhibitor
mechanical weed control
mode of action
mowing
nitrogen metabolism inhibitors
nonselective
nontarget
noxious weed

photosynthesis inhibitor
pigment inhibitor
postemergence
postharvest
preemergence
preplant
restricted use pesticide
Roundup
seed bank
seed dispersal
seedling growth inhibitor
selective
sprayer
systemic herbicide
terrestrial
toxicity
trade name
weed

Introduction

Of the nearly 300,000 plant species in the world, only about 1 percent have been cultivated. Therefore, many uncultivated plants have had the opportunity to grow where they are not wanted. Plants can be classified as **weeds** if they cause economic loss to a valuable crop, are harmful to humans and livestock, or are detrimental to wildlife and ecosystems. Before studying how weeds affect agriculture, it is important to understand weeds within the context of ecology. Many modern cropping systems are based on production of monocultures of annual crops that are grown in rows. Those systems that also employ annual soil disturbance are prone to invasion and proliferation of weed species. It is natural for multiple weed species to fill vacant space and to occupy a specific environmental niche. In these situations, competition for limited resources determines the dominant species. Unfortunately, the dominant plant species may not be the crop that humans are growing for food or fiber; therefore, control of weeds is a necessity (Table 15-1).

Describing Weeds

Weeds can be classified by their invasiveness, the environments in which they grow, their life cycles, and their taxonomy. These characteristics are important to learn because they form the foundation for weed control.

Noxious Weeds

Federal and state governments have categorized weeds that are especially undesirable as noxious. The Federal Noxious Weed Act (1974) defines a **noxious weed** as any living stage (including seeds and reproductive parts) of a parasitic or other kind of plant that is of foreign origin; is new or not widely prevalent in the United States; and can injure crops, other useful plants, livestock, poultry, or other interests of agriculture, including irrigation, navigation, fish and wildlife resources, or the public health. The list of more than 100 noxious weeds is available at http://www.aphis.usda.gov/.

Likewise, many states and counties have also identified noxious weeds as injurious to agriculture, public health, roads, the environment, and livestock. For example, Minnesota identifies prohibited, restricted, and secondary noxious weeds (Table 15-2).

TABLE 15-1

Potential of a single weed to reduce crop yields. 1 square foot = 0.1 square meter; 3 square feet = 0.3 square meter. *Adapted from Ross and Lembi (1999).*

Weed	Crop	Weeds per row or area	% crop-yield reduction
Giant foxtail	Soybeans	1 weed/ft	13
Velvetleaf	Soybeans	1 weed/3 ft	34
Smooth pigweed	Soybeans	1 weed/ft	25–27
Sicklepod	Soybeans	1 weed/ft	30
Palmer amaranth	Soybeans	1 weed/ft	64
Common cocklebur	Soybeans	1 weed/ft	87
Giant foxtail	Corn	1 weed/ft	7
Hemp dogbane	Corn	1 weed/ft	15
Hemp dogbane	Sorghum	1 weed/ft	30
Sicklepod	Cotton	1 weed/3 ft	40
Common cocklebur	Cotton	1 weed/3 ft	40–60
Wild oat	Sugar beet	1 weed/ft	22
Wild oat	Wheat	1 weed/ft^2	11

Invasive Plants

Invasive plants are nonnative plants (this includes noxious weeds) that become established in natural plant areas and replace native vegetation. Invasive plants have the ability to reproduce rapidly and to spread by seed or asexual means. These plant species have been introduced into new habitats where they do not naturally occur and are also called *nonnative*, *nonindigenous*, *alien*, or *exotic*. Though invasive plants can damage terrestrial and aquatic ecosystems, as well as cause economic loss to crops, they may not appear on the federal and state noxious weed lists described earlier in this chapter. Sometimes, invasive plants are cultivated ornamental and crop plants that have escaped into native ecosystems. Some examples of invasive plants in the United States include the following:

- **Common and glossy buckthorn (*Rhamnus* sp.).** These woody shrubs are native to Eurasia, were introduced as ornamentals, and have invaded woodlands.
- **Garlic mustard (*Alliaria petiolata*).** This forb was brought to the United States by colonists from Europe for cooking. It has invaded woodlands and eliminated native woodland plants.
- **Cheatgrass (*Bromus tectorum*).** This annual grass (also called *downy brome*) is native to Europe and Asia and has taken over large areas of dry grasslands in the West.

TABLE 15-2

Prohibited, restricted, and secondary noxious weed lists for Minnesota. These plants are prohibited because they are harmful to public health, the environment, public roads, crops, livestock, and other property. As required by Minnesota law, these weeds must be controlled or eradicated. *Minnesota Department of Agriculture (2010).*

Prohibited noxious weed list for Minnesota.

This is a partial list.

Common name	Botanical name
Field bindweed	*Convolvulus arvensis*
Hemp	*Cannabis sativa*
Purple loosestrife	*Lythrum salicaria* or *L. virgatum*
Garlic mustard	*Alliaria petiolata*
Poison ivy	*Toxicodendron radicans*
Leafy spurge	*Euphorbia esula*
Perennial sowthistle	*Sonchus arvensis*
Bull thistle	*Cirsium vulgare*
Canada thistle	*Crisium arvense*

Restricted noxious weed list for Minnesota.

These plants are those whose only feasible means of control is to prohibit their importation, sale, and transportation in the state.

Common name	Botanical name
Common buckthorn	*Rhamnus cathartica*
Glossy buckthorn	*Rhamnus frangula*

Secondary noxious weed list for Minnesota.

This is a partial list of plants that may be prohibited or restricted at the county level.

Common name	Botanical name
Jerusalem artichoke	*Helianthus tuberosus*
Wild buckwheat	*Polygonum convolvulus*
Burdock	*Arctium minus*
Common cocklebur	*Xanthium pennsylvanicum*
Giant foxtail	*Setaria faberii*
Jimsonweed	*Datura stramonium*
Kochia	*Kochia scoparia*
Common lambsquarters	*Chenopodium album*

- **Purple loosetrife (*Lythrum salicaria*).** This forb is a wetland perennial from Europe that was introduced by colonists as an ornamental and medicinal plant. It can eliminate most native wetland vegetation and clog waterways.
- **Kudzu (*Pueraria montana*).** This vine was introduced from Asia for erosion control, as a forage crop, and as an ornamental. In the southeastern United States, kudzu can fully overtake natural landscapes at rapid rates (Figure 15-1).
- **Leafy spurge (*Euphorbia esula*).** This creeping-perennial herbaceous species originated in Europe and Asia. Leafy spurge overtakes rangeland and pastures by crowding out grasses and other desirable species. Livestock avoid eating leafy spurge.



Peggy Greb, USDA-ARS.

FIGURE 15-1
Kudzu is a particularly destructive weed in the southeastern United States. Even large trees can be overtaken by this weed.

- **Eurasian watermilfoil (*Myriophyllum spicatum*).** This weed is an herbaceous aquatic plant native to Eurasia. It can compete effectively against native vegetation and clog waterways.

Terrestrial and Aquatic Weeds

Most weeds affecting crop production are **terrestrial** and live on land. Other weeds such as purple loosestrife, hydrilla, water hyacinth, and Eurasian watermilfoil are a problem in water. **Aquatic** weeds can destroy wetland ecosystems and interfere with the recreational use of waterways and lakes. They can also affect agricultural production by clogging irrigation canals.

Life Cycle

Like crop plants, weeds are annual, biennial, or perennial. Weeds with specific life cycles typically fit well into specific crop production practices that are similar.

Annual Weeds

Annuals are plants that complete their life cycle in one growing season. They thrive on frequently disturbed sites such as those occurring in corn and soybean production. Many annual weeds proliferate and persist because they have high levels of seed production (Table 15-3). Tillage and herbicides are effective at killing

TABLE 15-3

Approximate number of weed seeds produced per plant.
Adapted from Ross and Lembi (1999) and Renner (2000).

Weed species	Number of seeds/plant
Velvetleaf	1500
Yellow nutsedge	2400
Giant foxtail	2500
Pennsylvania smartweed	3000
Barnyard grass	7000
Common ragweed	15,000
Jimsonweed	23,400
Shepherd's purse	38,500
Curly dock	40,000
Common purslane	52,000
Common lambsquarters	72,000
Stinkgrass	82,000
Redroot pigweed	117,000
Black nightshade	178,000
Russian thistle	200,000
Witchweed	500,000

annual plants, but populations often redevelop from the soil seed bank during the season. Summer annual weeds germinate and grow during the summer months and compete with crops such as corn and soybean. Summer annual weeds include pigweeds, foxtails, jimson weed, and velvetleaf (Figures 15-2, 15-3, and 15-4). Winter annuals germinate in the fall, are vegetative during the winter months, and flower the following spring. Chickweed and shepherd's purse are examples of winter annual weeds.

Biennial Weeds

Biennials are plants that require two growing seasons to complete their life cycles. Biennials are vegetative in the first year and flower in the second year. They are not tolerant of tillage in the first or second year. Mowing in the second year before they flower can eliminate seed production. They persist best in permanent pastures, waterways, and roadside areas. This is the smallest group of weeds, though some such as common burdock are major problems in pasture. Other biennial species include musk thistle and bull thistle.



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FIGURE 15-2
Redroot pigweed is an annual broadleaf weed.

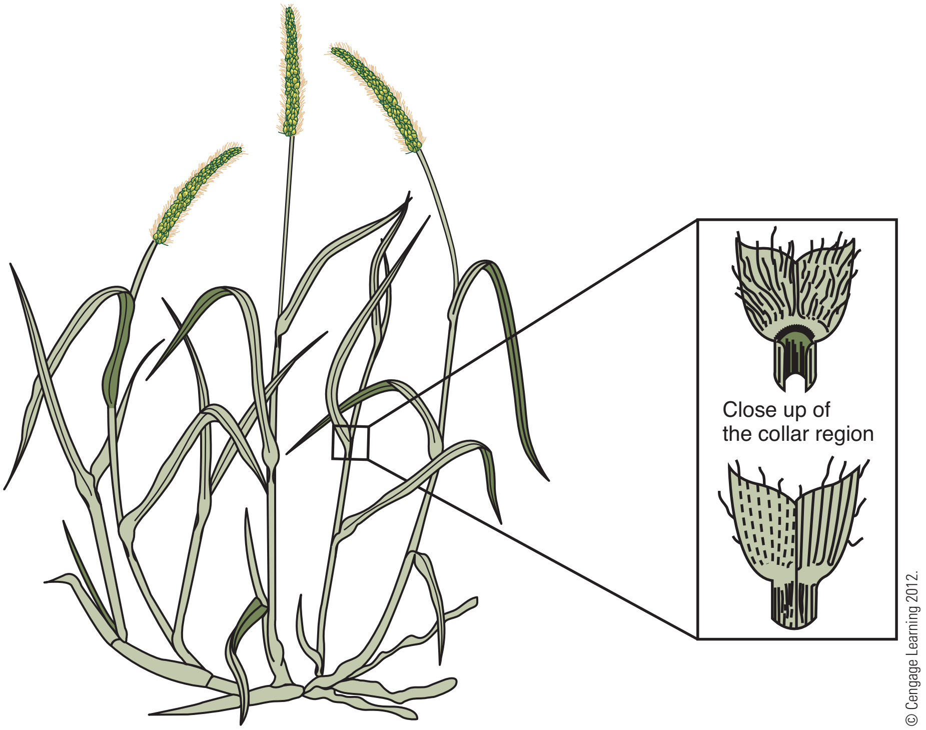


FIGURE 15-3
Yellow foxtail is an annual grass weed.



FIGURE 15-4
Jimsonweed is an annual broadleaf weed.

Perennial Weeds

Perennials are plants that live for three or more years. They have some specialized reproductive structures that allow for overwintering and long-term persistence such as crowns, rhizomes, and stolons (Figure 15-5). Once established, perennials are difficult to control except by herbicides. Many perennials can suffer defoliation by tillage and still regrow. Canada thistle, Bermuda grass, leafy spurge, dandelion, and johnsongrass can spread asexually and can regenerate from perennial

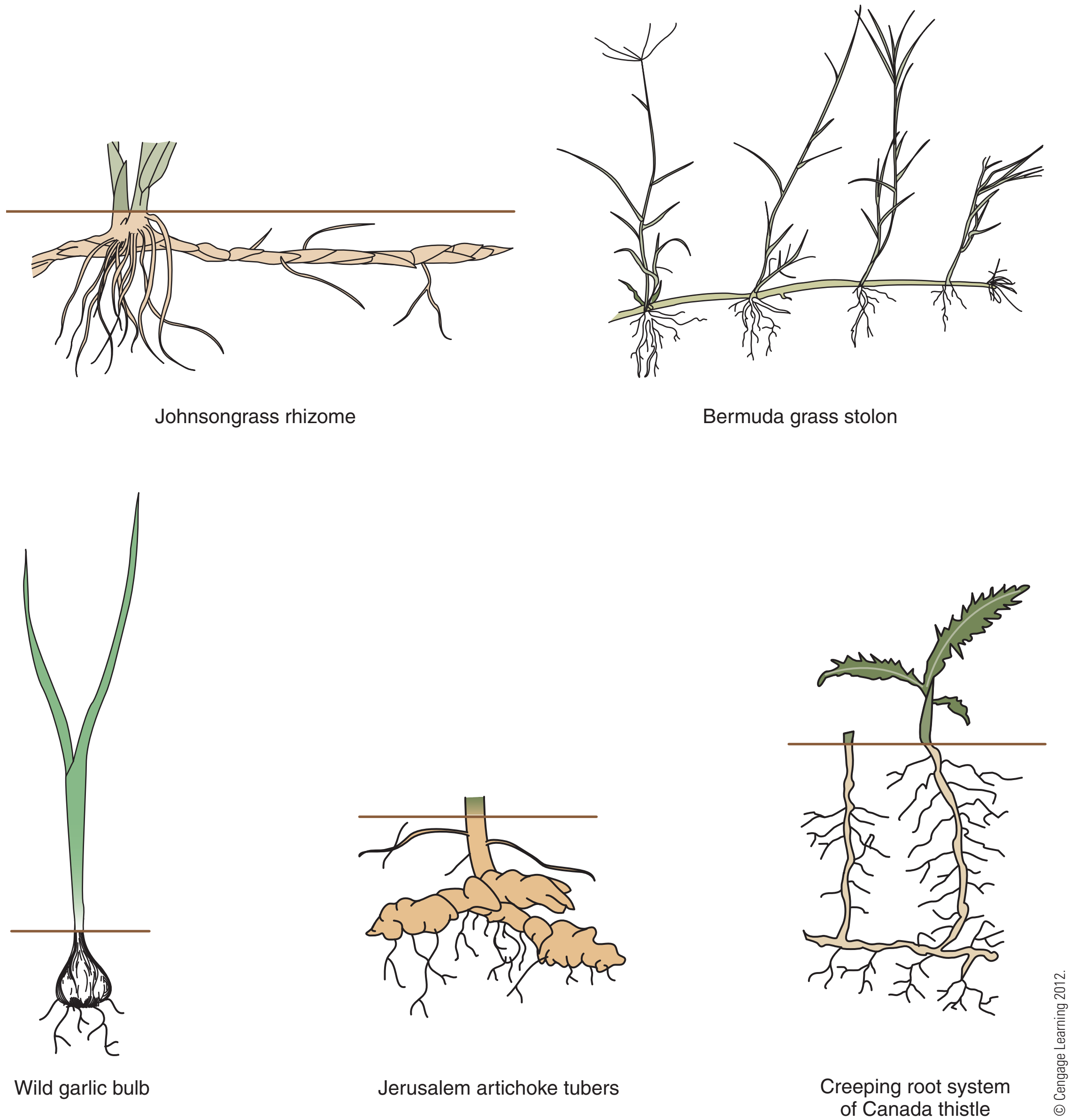


FIGURE 15-5 Asexual reproduction structures of perennial weeds.

structures (Figures 15-6 and 15-7). These types of perennials are best adapted to survive under a diversity of cropping systems.

Grasses and Broadleaves

Morphology is a critical factor in influencing the "weediness" of plants and how they respond to control measures. Chapter 7 describes the morphological features of plants. One major classification of weeds is whether they are monocots or dicots.

Monocot weeds affecting crop production systems are members of the grass and sedge families. The seeds contain a single cotyledon, and leaves are simple. The blade is the most obvious vegetative structure. Sometimes grasses are confused with sedges. Sedge stems are triangular or three-sided, whereas grass stems are rounded. During monocot germination, the seed remains underground, and only leaves emerge.

Dicots are frequently called **broadleaves**, in contrast to the grasses (monocots). They may have compound leaves. At germination, most dicot seeds emerge from below ground and are easier to kill by cultivation than grass seedlings are.

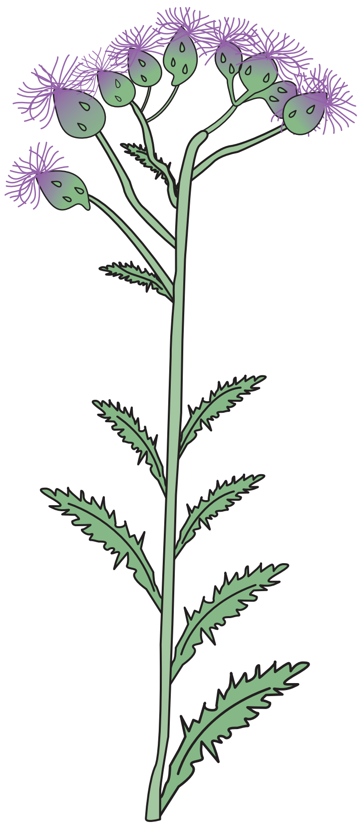


FIGURE 15-6
Canada thistle is a perennial weed.



FIGURE 15-7
Dandelion is a perennial broadleaf weed.

Weed Effects on Agriculture

Economically, weeds are the most important pests in crop production. They can reduce agricultural productivity and profitability in several ways (Figure 15-8 and Table 15-4).

- Weeds reduce the yield of cultivated crops by competing for essential resources.
- Weeds increase production costs during their control.
- Some weeds are allelopathic (see later in this chapter).
- Some weeds are parasitic and obtain their nutrients directly from other plants.
- Weeds devalue the primary crop.
- In their herbage, weeds may contain toxins that are harmful to livestock.

Weed Competition

Weeds compete with crops for light, water, and minerals. In annual cropping systems, effective competitors for light often have high levels of seedling vigor that allow for development of a weed canopy above the crop. The effect of weeds on crop growth and yield is typically greatest during crop establishment. Tall-growing weeds overgrow the crop and reduce the intensity and quality of the light that the crop receives (Figure 15-9).

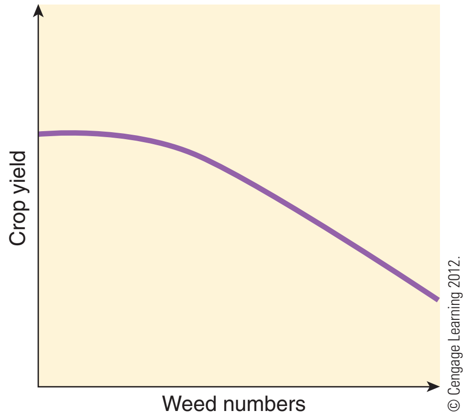


FIGURE 15-8 The general relationship between increasing weed density and crop yield.

TABLE 15-4

Effect of increasing weed densities on crop yields. *Adapted from Ross and Lembi (1999).*

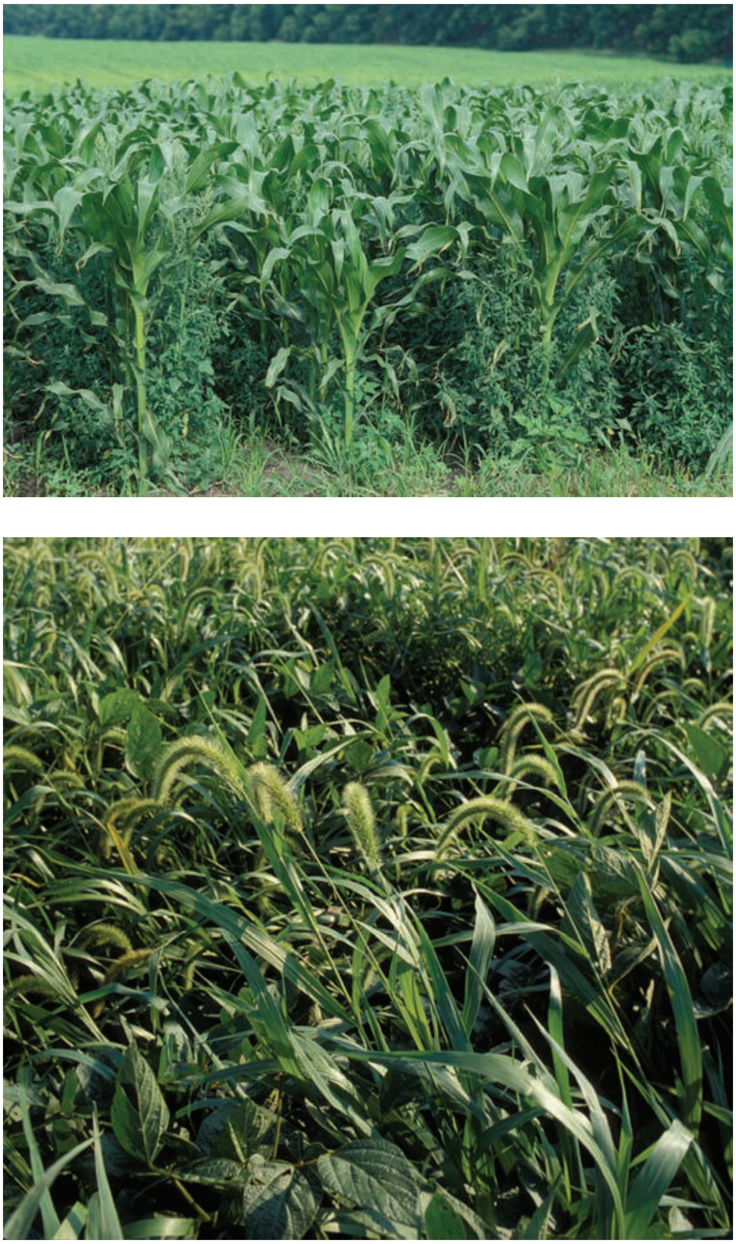
Velvetleaf in soybeans

Velvetleaf density		
plants/feet^2	plants/meter^2	% yield reduction
0.5	5	23
1	11	43
2	22	54
4	43	66

Common cocklebur in seed cotton

Cocklebur density		
plants/3- feet row	plants/meter row	% yield reduction
1	0.9	61
1.5	1.4	79
3	2.7	91
6	5.5	93

Allelopathy is the adverse effect of one plant on another due to production of a chemical inhibitor. Living or decaying plant tissue may excrete the chemicals. Relative to direct competition for resources, allelopathy is not a major cause of crop yield loss. Examples of weeds with the potential for allelopathy include Canada thistle, quackgrass, and wild oats. Allelopathy by weeds can reduce crop seed germination and seedling growth.



David L. Hansen, University of Minnesota.

FIGURE 15-9 Lambsquarters growing in corn and foxtail growing in soybean. Both weeds can reduce crop yields by competing for water, nutrients, and light.

Production Costs

Weeds increase the costs of crop production. The traditional approach to weed control using tillage required considerable labor inputs. To reduce labor costs, herbicides were developed and now are the primary form of weed control for most crops. However, herbicides still must be purchased and applied. For many important crops, nearly all the acreage grown receives herbicide application (Table 15-5). Often, herbicides are used in combination with some tillage practices.

TABLE 15-5

Herbicide use and cost for crops in the United States, 2005. *Adapted from Gianess and Reigner (2006)*.

Crop	% of crop treated	Tons/year	Tonnes/year	Total cost (millions $)
Corn	98	79,252	71,896	2600
Soybean	96	45,551	41,323	2400
Wheat	55	8,450	7666	500
Cotton	95	10,901	9889	507
Sorghum	91	6201	5625	126
Rice	98	7650	6940	248
Sunflower	95	800	726	27
Peanut	97	950	862	55
Canola	99	300	272	26
Field beans	99	1500	1361	44
Potato	93	1100	998	48
Sugar beet	98	3500	3175	128

Weeds Devalue Other Crops

Mixing weed seed with grain seed can result in economic loss if separation is not possible at harvest or later during processing. Grain contamination may decrease its value for livestock feeding or human use. Some examples include wild oat contamination of wheat and barley, and wild garlic in wheat. Another example of seed contamination can be seen during the production of forage grass, legume seed, and turf seed. The contamination of seed by other grass species or older varieties of the same species reduces the product's quality. Because of the similarity of seed size, such contaminants are difficult to separate.

Weed foliage can also be a contaminant. Grass and certain broadleaf weeds that are harvested with forage crops such as alfalfa reduce the nutritive value of the hay or silage. Grasses such as foxtail and barnyard grass that are present in harvested hay decrease its crude protein and reduce its consumption by livestock.

Interference with Harvesting

Weeds can interfere with harvesting operations such as combining. This occurs because weeds are often less mature than the crop to be harvested. As a result, the green mass of weeds can delay drying of the crop and can plug the cutting and threshing machinery. An example is invasion of a wheat field with lambsquarters or water hemp that is still actively growing when the wheat is harvested.

TABLE 15-6

Plants containing toxic compounds. *Adapted from Kingsbury (1964).*

Plant	Compound	Plant part	Effect on livestock
Cocklebur	Hydroquinone	Seeds and herbage	Nausea, poor gain
Lambsquarters	Nitrates	Herbage	Respiratory failure, death
Halogeton	Oxalates	Herbage	Kidney failure
Hoary alyssum	Unknown	Herbage	Fever, founder in horses
Nightshade	Alkaloid	Herbage and green berries	Diarrhea
Poison ivy	Urushiol	Herbage and roots	Dermatitis
Water hemlock	Cicutoxin	Roots and herbage	Death
White snakeroot	Retinol	Herbage	Kidney failure

Weeds Containing Toxic Chemicals

Some plants contain chemicals in their herbage, causing it to be unpalatable or toxic (Table 15-6). These chemicals are naturally occurring metabolic products and are sometimes considered a defense against herbivory. Grazing livestock do not usually consume toxic herbage unless forced to do so, as in overgrazing situations. Sometimes, toxicity can occur when poisonous plants are made into hay.

Human Health Issues

Some plants cause specific human health issues through exposure to plant parts or seed. For example, contact with poison ivy and poison oak can result in severe dermatitis because of the poisonous volatile oils. Exposure to the volatile oils can also occur through inhalation of smoke that contains airborne resin resulting from burning leaves and stems of poison ivy. Numerous weeds produce pollen that causes allergic reactions in humans. For example, allergies to common and giant ragweed are prevalent.

Humans can also experience health issues from directly or indirectly ingesting poisonous plants (Table 15-7). A noteworthy example occurs when the fungus *Claviceps purpurea* infects a commonly grown grain, rye. The resulting sclerotia from the fungus replaces the grain and is called *ergot*. Ergot contains poisonous alkaloids and lysergic acid. The hallucinations and other bizarre behavior associated with the Salem Witch Trials in the 1690s were related to ingestion of ergot from rye grain made into bread. Ingestion of ergot can cause convulsions, hallucinations, and death. In general, ingestion of poisonous plants causes a diversity of symptoms related to the poisonous components.

TABLE 15-7

Examples of human poisonings through ingestion or inhalation of toxins from weeds. *Adapted from Kingsbury (1964).*

Plant	Active ingredient	Part	Symptoms
Hemp (*Cannabis sativa L.*)	Tetrahydro cannabinol	Leaves, flowers	Hallucinations, confusion
Jimsonweed	Indole alkaloids	Seed leaves	Delirium, convulsions, coma
Nightshade	Solanine alkaloids	Berries leaves	Delirium, convulsions, coma
Water hemlock (*Cicuta spp.*)	Cicutoxin, an alcohol	Root, stem	Convulsions, death
White snakeroot (*Eupatorium rugosum*)	Tremetol, an oil	Leaves and stems	Milk sickness, trembles, liver failure, death



FIGURE 15-10
White snakeroot is a poisonous weed that contains tremetol, an oil that is toxic to livestock and humans. The primary route of entry to humans is through milk obtained from cattle grazing the weed.

Milk sickness is a well-documented historic illness associated with consumption of milk from cows that consumed white snakeroot, a perennial plant that once thrived in moist woodlands (Figure 15-10). White snakeroot contains a toxic oil, tremetol, that can be passed from cows to humans as a constituent of the milk fat. Humans who consume contaminated milk can become very sick, and they often die. Symptoms include vomiting, muscle weakness, liver failure, and severe intestinal pain. Milk sickness occurred frequently in the early 1800s, when unfenced cattle often pastured on wooded areas and families drank milk from only a few cows. Milk sickness is rare today because most dairy cows do not graze woodlands where white snakeroot grows.

Unique Traits of Some Weeds

Weeds that impact crop production usually have one or more traits that contribute to their undesirable effects.

Seed Production

In contrast to most cultivated crops, many weeds produce small seeds and very high numbers of seed (see Table 15-3). High seed numbers provide an opportunity for weed populations to rapidly increase. They also ensure the survival of the species, should adverse conditions or crop management eliminate some members of the population. For example, a portion of the weed seeds might germinate in early spring and be killed by tillage immediately before planting. Another group of the remaining weed seeds can then germinate and compete with the crop.

Seed Dormancy

Weed seeds can have a long dormancy period and a staggered rate of seed germination. This enables weed seed to persist and remain viable in the soil for long periods (Table 15-8). Yearly disturbances in populations will eliminate some, but not all, of a weed species. The total dormant and nondormant seed accumulated in the soil is called the **seed bank**. This soil seed bank provides a reservoir for seed for the

TABLE 15-8

Longevity of weed seeds buried in the soil. *Adapted from Ross and Lembi (1999).*

Weed	Years
Quackgrass	1–6
Common milkweed	3
Wild oat	4–7
Shattercane	10
Common cocklebur	16
Foxtail	20
Field bindweed	20+
Johnsongrass	20
Canada thistle	21
Jimsonweed	40
Common lambsquarters	40
Redroot pigweed	40
Velvetleaf	40

perpetuation of the weed populations. With each tillage of the soil, seeds are brought to the soil surface and, if conditions are favorable, a new population of weeds germinates. Seed of some weed species can remain dormant for many years until environmental and cultural conditions are appropriate for it to establish.

Seed Dispersal

Weed seeds are dispersed by numerous means including water, wind, animals, and humans. Some plant species such as dandelion and milkweed have unique appendages that aid movement of the seed by wind. Others, such as kochia and Russian thistle, deposit seed as the detached whole plant tumbles across the land (hence the name *tumbleweeds*).

Unique appendages on some seeds promote attachment to fur and clothing, and they aid in seed dispersal (Figure 15-11). The unique, hooked attachment mechanism of burdock is so efficient, humans have copied the design in the development of Velcro for use in clothing.

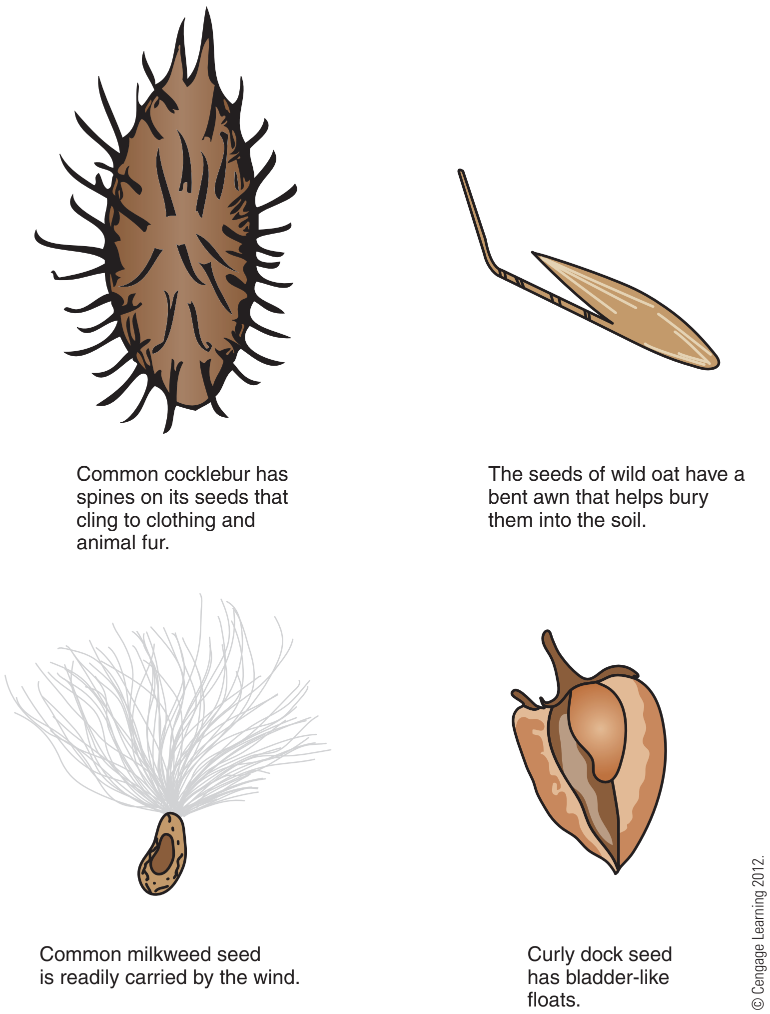


FIGURE 15-11
Unique seed appendages of some weeds. The appendages aid in dispersion of the seed.

Domesticated and wild animals play a significant role in the movement of weed seeds. Grazing cattle and sheep frequently consume weed seeds. A portion of the weed seeds is deposited undamaged in the manure and so is moved to a new location in the field. Likewise, weed seeds fed to confined animals may be moved to a considerable distance as the manure is spread on fields. Wild animals may move weed seeds through ingestion and manure deposition or following attachment to fur. A major factor in movement of purple loosestrife, an aquatic weed, is transport of the small seeds attached to the feet of ducks and geese.

Vegetative Reproduction

Vegetative (asexual) reproductive strategies enable spreading of the weed from the original plant, without the use of seed. Examples include quackgrass and johnsongrass (both have rhizomes); leafy spurge and Canada thistle (both have creeping roots); and Bermuda grass (has stolons). Plants with asexual reproduction also can survive stress due to tillage and severe defoliation better than plants that rely on seeds for reproduction. Rather than destroying these plants, tillage cuts the rhizomes and stolons into pieces, which then can regenerate into many new plants.

Weed Biotypes

Many weeds have the potential to adjust their form to adapt to environmental and management practices. Populations of weeds that develop special traits such as herbicide resistance are called **biotypes**. For example, quackgrass can survive in closely mowed or grazed pastures by changing to a low-growing form. Some weeds also develop resistance to herbicides by using detoxifying or morphological modifications.

Reducing the Risk of Losses Due to Weeds

There are various approaches to reduce the risks associated with weeds. Preventing weed establishment is the first line of defense in reducing weed problems. Control practices include herbicides, cultural, mechanical, and biological approaches.

Weed Prevention

There are several layers of responsibility for prevention of weeds.

U.S. Government

The Animal and Plant Health Inspection Service (APHIS) of the USDA prevents the introduction of parasitic plant pests and federal noxious weeds into the United States. APHIS excludes and eradicates newly introduced weeds that pose a risk to agriculture or the environment. APHIS may cooperate with other agencies to achieve environmentally sound, integrated pest management against introduced invasive plants. The U.S. Federal Seed Act aids in preventing the spread of weeds by requiring labeling of seed by variety and point of origin. Along with the labeling of seed, this act requires identification of the percentage of weed seed. Any noxious weed seeds present in the seed must be identified.

State Government

The federal government encourages states to have parallel laws to prevent and control noxious weeds. In addition, many counties and local jurisdictions have laws related to weed control.

Farmers

Farmers should use only weed-free seeds and manage their farms to prevent weeds from producing seed. Seed production should be prevented in actively farmed fields and also in road ditches, field borders, fence lines, waterways, and wood lots that may serve as reservoirs for seeds to re-infest fields.

Herbicides

Herbicides are the primary method of weed control in conventional agriculture. An **herbicide** is a chemical used for killing or injuring plants (Figure 15-12). The name is derived from the Latin words *herba*, which means plant, and *cida*, which means to kill. Modern herbicides are synthetic chemical compounds with specific mechanisms for killing plants. Although in the past compounds such as salt, petroleum oils, and arsenic compounds were sometimes used as herbicides, the widespread development of modern herbicides did not occur until World War II. Today, more than 100 major herbicides are marketed in the United States. Herbicides are a key component of the technological age of agriculture. The following lists some advantages of herbicides compared with alternative approaches:

- Production costs per acre are reduced versus mechanical weed control or hand weeding.
- Herbicides provide greater flexibility in timing of weed control than mechanical approaches and can remove weeds from within rows.
- Herbicides have been developed that will selectively remove weeds from turf and forages without damaging the crop.
- Herbicides can reduce or eliminate the need for mechanical tillage. For example, in no-till planting systems, herbicides are used to control weeds, and the crop is planted directly into the residue of the previous crop.

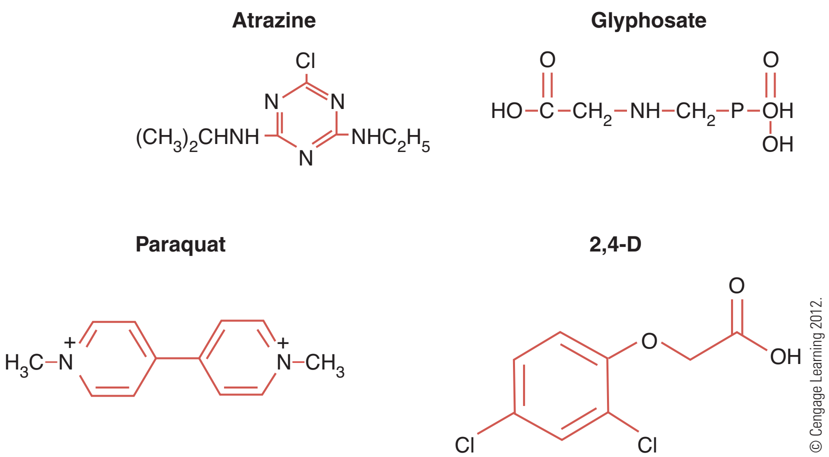


FIGURE 15-12 The chemical structures of some important herbicides.

- Specific herbicides can be used to kill tenacious perennials such as nutsedge, Canada thistle, quackgrass, and poison ivy that are challenging to kill by using tillage or mowing.
- Some herbicides can persist in the soil to provide long-term control of weeds.

Use of herbicide technology can have negative consequences, though many of these consequences can be avoided through proper use as indicated on **Environmental Protection Agency (EPA)**-approved labels. Some challenges associated with herbicide use include the following:

- Herbicides can potentially kill or injure **nontarget** plants. Nontarget plants are those other than weeds.
- Some herbicides can contaminate water supplies used by humans and farm animals.
- Herbicides can persist in the soil and injure succeeding crops.
- Herbicide use can lead to development of resistant weed species that are difficult to control.
- Herbicides may fail to control weeds due to human error and unpredictable environmental conditions.

Herbicides are used more than other pesticides such as insecticides or fungicides (Figure 15-13). Nearly 300 million pounds (136 million kilograms) of herbicides are applied annually to nearly 100 percent of the corn, soybean, potato, and cotton acres in the United States. They are also used extensively for other crops such as wheat and alfalfa. Annual application costs are nearly $6 billion (Figure 15-14). Herbicide application in total weight to all crops has decreased since the 1980s due to new herbicides, refinement in application rates, and increased use of crops with resistance to glyphosate (see the following discussion).

For corn, cotton, and soybean crops, **glyphosate**, a nonselective herbicide, is the most widely used herbicide (Figure 15-15). Glyphosate can be used to control weeds in crops with tolerance to glyphosate, but it also has applications such as

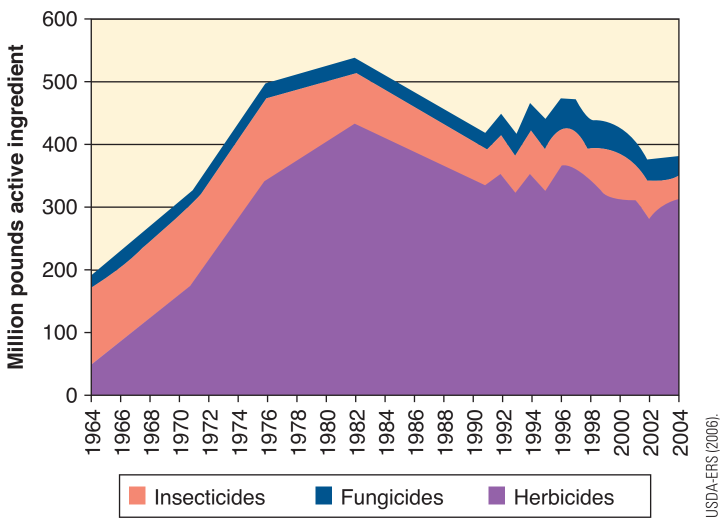


FIGURE 15-13 The amount of pesticides used in the United States. Herbicides are the largest group of pesticides used on crops. Overall quantities have decreased. 1 million pounds = 0.45 million kilogram.

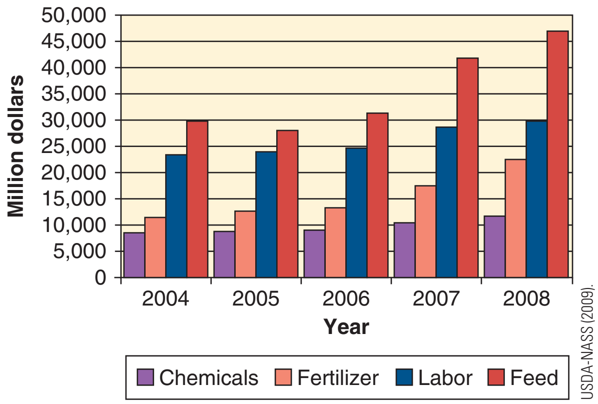


FIGURE 15-14
U.S. farm-production expenditures for chemicals, fertilizer, labor, and feed in 2004 to 2008. Chemicals, including herbicides and other pesticides, contribute a significant amount to farm production expenditures.

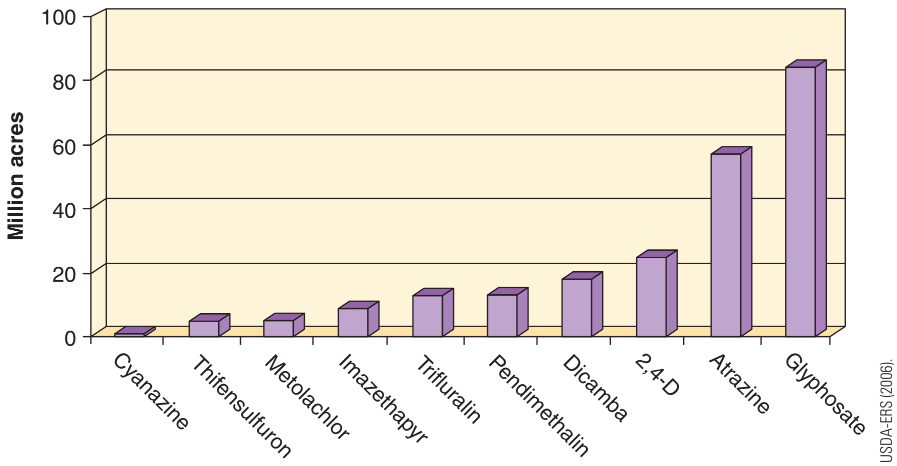


FIGURE 15-15
The most widely used herbicides in the United States. 1 million acres = 400,000 hectares.

chemical fallowing (see Chapter 13). However, most crops receive applications of a specific group of herbicides that are targeted to a particular combination of weeds and crops.

Herbicide Tolerant Crops

Genetic engineering of crops has resulted in the development of crops with **herbicide tolerance** and insect resistance. Incorporating resistance to glyphosate, or **Roundup** (plants with this trait are called *Roundup Ready*), is the most widely used herbicide tolerance technology. Roundup Ready varieties of soybean, corn, cotton, canola, and alfalfa have been developed. The Roundup Ready technology integrates genetic resistance to glyphosate into crops by inserting a bacterial gene. This trait is particularly attractive to producers because Roundup is a relatively low-cost herbicide that kills a diversity of weeds without damaging crops with the resistant trait. It can be applied following emergence of the weeds and crops. Therefore, it is especially adapted to planting practices that use conservation tillage and no-tillage. It is sequestered in the soil and on foliage of plants, and it has minimal environmental impact.

Adoption of genetically engineered (GE) soybeans, corn, and cotton by U.S. farmers has increased since the first soybean varieties became available com-

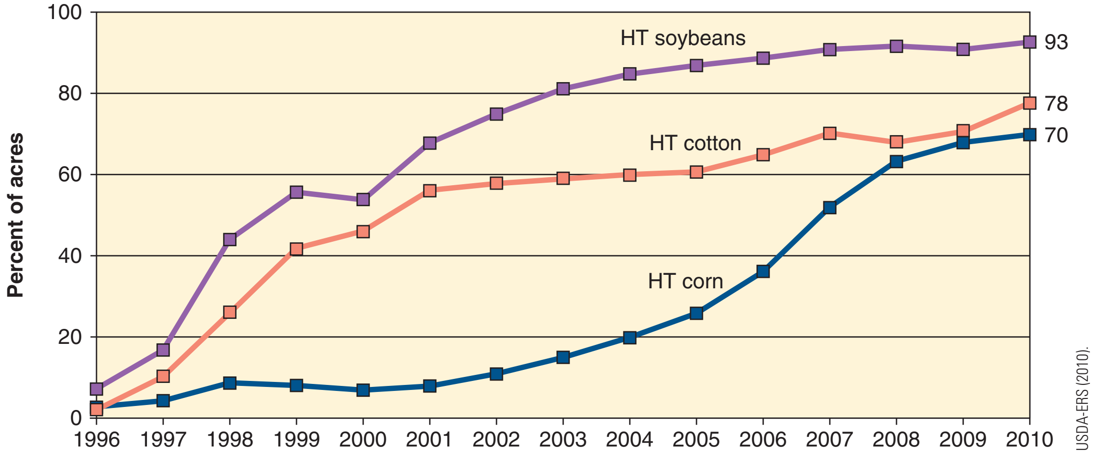


FIGURE 15-16 Adoption of genetically engineered herbicide tolerant (HT) crops in the United States has increased significantly since their introduction in 1996.

mercially in 1996 (Figure 15-16). Acreage of Roundup Ready herbicide-tolerant soybean has expanded most rapidly. About 93 percent of soybean acreage, 70 percent of corn acreage, and 78 percent of cotton acreage are planted with herbicide-tolerant varieties. Many cotton and corn varieties also have been genetically engineered to have insect tolerance.

EPA Approval of Herbicides

For an herbicide to be sold in the United States, the EPA must approve it. The process of developing and gaining approval of a new herbicide takes many years and considerable expense. A company requesting approval of a new herbicide must provide information on the formulation and chemistry; on environmental and ecosystem impacts; and on human, animal, and nontarget plant impacts. Human and animal toxicity information is especially important. EPA approval is given only following careful evaluation of the benefits and risks of the new herbicide. Herbicides must also be registered with state agencies such as a state's department of agriculture. State agencies regulate herbicide use and may install special restrictions on its use.

The Herbicide/Pesticide Label

A key part of the registration process is the development of a product label that is used in the identification and the marketing of the herbicide. The label presents information directly on the packaging and has several key features (Figure 15-17).

1. **Identification.** Herbicides and other pesticides typically have three names for identification: the brand or **trade name** (used for marketing), the common name, and the chemical name. For example:
   - Trade name: Aatrex or Atrazine

     Common name: Atrazine

     Chemical name: 2-Chloro-4-ethylamino-6-isopropylamino-1,3,5-triazine

(1) WACKER - MPL

(4) A Restricted Use Herbicide (2)

Dry Flowable (3)

For Weed Control in Potato

WACKER® is recommended for postemergence control of broadleaf and grass weeds in potatoes.

This product is a water dispersible granule containing 50% active ingredients by weight.

(5)

Active Ingredient	*By Weight*
Triflusulfuron cecil, 2-dicamo-amino H_2O	50%
Inert Ingredients	50%
TOTAL	100%

EPA Reg. No. 000-000

Net contents: One gallon

PRECAUTIONARY STATEMENTS

(7) CAUTION

HAZARDS TO HUMANS AND DOMESTIC ANIMALS

(8)

CAUTION! Avoid contact with skin, eyes and clothing. In case of contact with eyes, immediately flush with plenty of water.

For medical emergencies involving this product, call toll free 1-800-000-000

KEEP OUT OF REACH OF CHILDREN

(9) FIRST AID

IF IN EYES: Hold eye open and rinse slowly and gently with water for 15–20 minutes. Call a poison control center for treatment advice.

IF ON SKIN OR CLOTHING: Take off contaminated clothing. Rinse skin immediately with plenty of water for 15–20 minutes. Call a poison control center for treatment advice.

Have the product container or label with you when calling a poison control center or doctor, or going for treatment.

(9) PERSONAL PROTECTIVE EQUIPMENT

Applicators and other handlers must wear:

Long-sleeve shirt and long pants.
Chemical Resistant Gloves Category A (such as butyl rubber, natural rubber, neoprene rubber, or nitrile rubber), all ≥ 14 mls.
Shoes plus socks.

USER SAFETY RECOMMENDATIONS

USERS SHOULD: Wash hands before eating, drinking, chewing gum, using tobacco, or using the toilet

ENVIROMENTAL HAZARDS

Do not apply directly to water, or to areas where surface water is present, or to intertidal areas below the mean high water mark.

(9) STORAGE AND DISPOSAL

Storage: Store product in cool, dry place in original container only. Do not contaminate water, other pesticides, fertilizer, food or feed in storage.
Product Disposal: Do not contaminate water, food or feed by disposal. Waste resulting from the use of this product may be disposed of on site or at an approved waste disposal facility.

FIGURE 15-17 A portion of a fictional herbicide label for a product marketed as Wacker MPL. A label can also include supplemental printed material.

- Trade name: Cyclone, Gramoxone Extra, Starfire
  Common name: Paraquat
  Chemical name: 1,1′-dimethyl-4,4′-bipyridinium iron (dichloride salt)
- Trade name: Roundup, Roundup Ultramax, Rodeo
  Common name: Glyphosate
  Chemical name: *N*-(phosphonomethyl) glycine

2. **Type of pesticide.** Herbicides, fungicides (kill fungi), insecticides (kill insects), nematicides (kill nematodes), and other pesticides must be labeled as such.
3. **Formulation.** Formulation describes the mixture of the **active ingredient** with compatible **inert ingredients**. Inert ingredients are added to make handling easier, to facilitate application, and to increase the active ingredient's activity. Most herbicides are formulated to allow spraying. These formulations are solutions, concentrates, liquids, and soluble powders. Dust, aerosol, and pellets are other examples of formulations. Inert materials include adjuvants, which are materials such as suspension or dispersion agents. These are mixed with active ingredients to improve their performance.
4. **Classification.** The EPA classifies pesticides into two groups. **General use pesticides** are those products that present little danger to humans or the environment when applied according to label directions. These products are sold at local retailers and are accessible to the general public. **Restricted use pesticides** are harmful to humans or to the environment, even when used as directed. In many states, only licensed applicators can purchase and apply these products.
5. **Ingredients.** Herbicides contain active and inactive ingredients. Active ingredients are the toxic ingredients, whereas inactive ingredients are compounds added as carriers or stabilizers.
6. **Directions for use.** Herbicides must be used in a safe manner. It is a violation of federal law to use them in a manner inconsistent with their labeling.
7. **Warnings and precautions.** These are provided as signal words that are related to toxicity categories developed by the Environmental Protection Agency (Table 15-9). The level of **toxicity** is based on oral and dermal toxicity

TABLE 15-9

EPA toxicity categories and their effects. *EPA (2010)*.

	I	II	III	IV
Oral LD_{50}	Up to and including 50 mg/kg	From 50 to 500 mg/kg	From 500 to 5000 mg/kg	Greater than 5000 mg/kg
Inhalation LC_{50}	Up to and including 0.2 mg/L	From 0.2 to 2 mg/L	From 2 to 20 mg/L	Greater than 20 mg/L
Dermal LD_{50}	Up to and including 200 mg/kg	From 200 to 2000 mg/kg	From 2000 to 20,000 mg/L	Greater than 20,000 mg/kg
Eye effects	Corrosive; corneal opacity not reversible within 7 days	Corneal opacity reversible within 7 days; irritation persisting for 7 days	No corneal opacity; irritation reversible within 7 days	No irritation
Skin effects	Corrosive	Severe irritation at 72 hours	Moderate irritation at 72 hours	Mild or slight irritation at 72 hours

using the measure of LD_{50} or LC_{50}. **LD_{50}** is the single dose in milligrams per kilogram taken that will kill 50 percent of a test population. **LC_{50}** is the concentration in air or water that will kill 50 percent of the population. *Danger* indicates that the herbicide is highly hazardous and is in Toxicity Category I. A taste to a teaspoonful is the amount that will kill an average adult. A skull and crossbones and an additional signal word *Poison* appears on the labels of the most acutely toxic pesticides. *Warning* indicates the product is moderately hazardous and is in Toxicity Category II. A teaspoonful to an ounce is the amount that will kill an average adult. *Caution* indicates the product is slightly hazardous and is in Toxicity Category III or IV. It would take over an ounce to kill an average adult.

8. Routes of entry—hazards to humans. Pesticides can enter the body by four primary sites of entry.
   - **Oral exposure.** Herbicides can sometimes be accidentally consumed with food or water. Pesticide containers should not be reused for carrying food or water.
   - **Dermal exposure.** Skin (the dermis) is responsible for a large proportion of pesticide exposure. The body should be protected as indicated on the label.
   - **Inhalation exposure.** Inhalation of particles, droplets, or fumes is hazardous because pesticides can be absorbed rapidly through the lungs. Masks and other appropriate equipment to protect the respiratory system are recommended when using many herbicides.
   - **Eye exposure.** Herbicides can be absorbed through the thin eye membranes. Damage to the eyes can occur.
9. Other important label components include protective clothing and equipment (Figure 15-18), safe handling, first aid, environmental hazards, physical or chemical hazards, re-entry intervals or restricted-entry intervals, and storage and disposal.



Tim McCabe, USDA-NCRS.

FIGURE 15-18
To prevent exposure to pesticides, it is important to wear appropriate protective clothing as indicated on the pesticide label.

How Herbicides Kill or Injure Plants

The **mode of action** describes the biochemical mechanism that herbicides use to kill plants. Knowledge of the mode of action is helpful when using herbicides to achieve effective weed control. The mode of action for an herbicide can be selective or nonselective related to the weeds they affect. **Selective** herbicides affect only certain species, whereas **nonselective** ones affect almost all plants. Here are some modes of action for widely used herbicides.

1. **Growth regulators** disrupt plant growth by interfering with hormones and protein synthesis. These herbicides are mostly taken up by the foliage but can be absorbed by the roots. They are translocated in the plant's vascular system.

   Example: 2,4-D for broadleaf weed control such as dandelion, pigweed, and lambsquarters in fields and lawns.

2. **Amino acid synthesis inhibitors** disable enzymes responsible for specific amino acid synthesis. Therefore, proteins important for plant growth are not formed. These herbicides are taken up by the foliage and translocated in plants. They are effective against annuals as well as perennial species.

   Example: Imazethapyr (Pursuit) for selective control of grass weeds in legumes such as soybean and alfalfa.

   Example: Glyphosate (Roundup) for nonselective weed control in many crops. As mentioned before, some transgenic crops have Roundup resistance.

3. **Lipid synthesis inhibitors** prevent the formation of fatty acids that are important for lipid synthesis. Lipids play key roles in cell membranes and also energy storage. These herbicides are taken up by the foliage and translocated in the plant.

   Example: Sethoxydim (Poast) for control of grass weeds such as foxtail and barnyard grass in soybean and alfalfa.

4. **Nitrogen metabolism inhibitors** impede the enzyme that helps produce glutamine, which is required for nitrogen metabolism.

   Example: Glufosinate (Liberty) for nonselective weed control in crops that have the glufosinate-resistant trait including canola, corn, soybean, and cotton.

5. **Seedling growth inhibitors** affect growth of the roots and shoots of germinating seedlings. They are active at multiple sites in a plant and affect cell division and other processes such as photosynthesis. These herbicides are taken up by the roots and developing shoots as they emerge through the soil and must be soil applied before germination of the weed seed.

   Example: Trifluralin (Treflan) for control of grasses and some broadleaf weeds in soybean and alfalfa.

   Example: Alachlor (Lasso) for control of grasses and some broadleaf weeds in soybean, corn, and sunflower.

6. **Photosynthesis inhibitors** prevent plants from conducting photosynthesis and producing energy by binding to the chloroplasts.

   Example: Atrazine for control of susceptible grass and broadleaf weeds in corn and sorghum. Atrazine can be taken up by plant's roots through the soil and the plant's foliage.



Atrazine Controversy

Atrazine, a triazine herbicide, is an important herbicide used in the United States and around the world. It is described chemically as 2-Chloro-4-ethylamino-6-isopropylamino-1,3,5-triazine. Developed in the 1950s by Syngenta, atrazine was first registered for use in the United States in 1958. Atrazine quickly became one of the most popular herbicides, particularly for corn production, because of its ability to control a wide variety of broadleaf and grass weeds throughout the growing season and not injuring corn crops even at high rates of application. Atrazine also has very low water solubility, which makes it relatively stable in the soil profile, and able to withstand adverse weather conditions. Atrazine is commonly applied as a preemergent herbicide, sprayed after crops are seeded but before the weeds and crops emerge. Today, around 88 percent of all atrazine use is for weed control in corn, and some estimates of use in the United States amount to over 76 million pounds (35 million kilograms) of product used per year. Since it is so effective at controlling weeds as a preemergent herbicide, farmers and researchers have observed clear yield benefits by utilizing it. In addition, atrazine is a frequently used herbicide in no-till and conservation tillage corn acres in the United States.

Atrazine has been at the center of a number of environmental and health investigations, and much conflicting research has focused on the herbicide and its effects on the environment. One of the main concerns with atrazine is leaching and accumulation in surface water and groundwater, especially in rural agricultural regions where use is particularly high. Atrazine does not readily break down in the environment, and frequent applications can increase the risk of water contamination despite its low mobility in the soil. While government-sponsored studies have found atrazine levels in water throughout the Midwest to be below recommended levels, scientific study has linked human atrazine exposure, especially at chronic low-levels, to endocrine disruption, reproductive impairment, and even mitochondrial dysfunction and insulin resistance.

Another area of concern with atrazine is its effect on the health and reproductive viability of amphibians, fish, and other aquatic animals. Some research has observed that chronic, low doses of atrazine exposure can cause male sterilization, feminization, hermaphroditism, and lead to reduced endocrine and reproductive functioning in amphibians. The EPA determined in 2006 that there is not enough information to state that atrazine poses a health risk to adults, children, or amphibian reproduction. However, the EPA began reviewing atrazine again in 2009 and there is potential for a ban (it is currently banned in the European Union). Some researchers believe that a national ban on atrazine would have significant financial effects on corn growers and the economy. This issue is a volatile one for proponents and opponents on both sides.

7. **Cell membrane disruptors** are herbicides that destroy plant foliage by directly rupturing cell membranes. They are quick-acting contact herbicides that require contact with foliage and sunlight for activation.

   Example: Paraquat (Gramoxone Extra) for nonselective weed control. Because of its fast activity, Paraquat is called a burndown herbicide. It is very effective against annual plants, but perennial plants will often regrow from crowns, stolons, or rhizomes.

8. **Pigment inhibitors** prevent plants from forming the chlorophyll that is essential for photosynthesis. Plants turn white and often become translucent.

   Example: Clomazone (Command) for control of some annual grasses and broadleaves in soybeans. It is especially effective against velvetleaf. It is taken up by plant roots and shoots.

Herbicide Application

Sufficient concentrations of herbicides must be applied in an appropriate manner for herbicides to be effective. The mode of action often dictates the application approach.

Preplant herbicides are applied to the soil before planting. They target germinating weed seeds and seedlings. Some preplant herbicides require incorporation by tillage to avoid loss due to volatilization. Because most weed seeds are located in the top few inches of the soil, shallow incorporation is important. Preplant herbicides are taken up by the plant root or the shoots while they are still underground. An example of a preplant herbicide is Treflan that is used for weed control in alfalfa and soybean.

Preemergence herbicides are applied to the soil after the crop has been planted but before the crop or weeds have emerged. These herbicides need to be leached into the soil by rainfall or irrigation. As with preplant herbicides, preemergence herbicides are taken up by weed roots or germinating shoots. Atrazine is a preemergence herbicide that controls many broadleaf and grassy weeds.

Postemergence herbicides are applied after the crop or weeds have emerged. These herbicides most often depend on foliar contact for activity. Postemergence herbicides are now the most widely used types of herbicides because they have a longer time frame in which they can be applied relative to preplant and preemergence herbicides. Glyphosate and Poast are examples of postemergence herbicides with activity against grassy and broadleaf weeds (Figure 15-19).

Postharvest herbicides are applied after harvest but before tillage. Most herbicides applied after the harvest kill weeds that have already germinated, so foliar contact is necessary. Herbicides such as glyphosate are especially effective against perennial weeds.

Contact versus Systemic

Also related to application, herbicides can be classified as *contact* or *systemic* based on whether they are translocated. **Contact herbicides** are applied to foliage, and they kill plants by destroying cells they come into contact with. They do not move throughout the plant. Herbicides with a cell-wall disruption mode of action are contact herbicides. Fuel oil and Paraquat are contact herbicides. Alternatively, **systemic herbicides** are taken up by the shoot or roots and are translocated throughout the plant in the vascular system. Systemic herbicides are used for



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Lynn Betts, USDA-NRCS.

FIGURE 15-19
In minimum tillage systems for corn seeded into corn residue (above) and soybean seeded into small grains residue (below), postemergence herbicides are commonly used.

control of perennial weeds because they can move throughout the plant to perennial plant parts such as stolons, rhizomes, and crowns. Glyphosate and 2,4-D are systematic herbicides.

How Are Herbicides Applied?

Most herbicides are applied by spraying liquid formulations from self-propelled or tractor-pulled spraying equipment. A typical **sprayer** consists of a tank for carrying liquid, pumps to provide pressure to move the liquid from the tank to the spray nozzles, a pressure regulator and gauge to maintain a constant pressure, and appropriate nozzles (Figures 15-20, 15-21, and 15-22).

Herbicide Resistance

Excessive use of a single herbicide can result in the development of resistant weeds if sound management is not used. **Herbicide resistance** is described as the tolerance of herbicides by weed species that were once susceptible. More than 100 weed

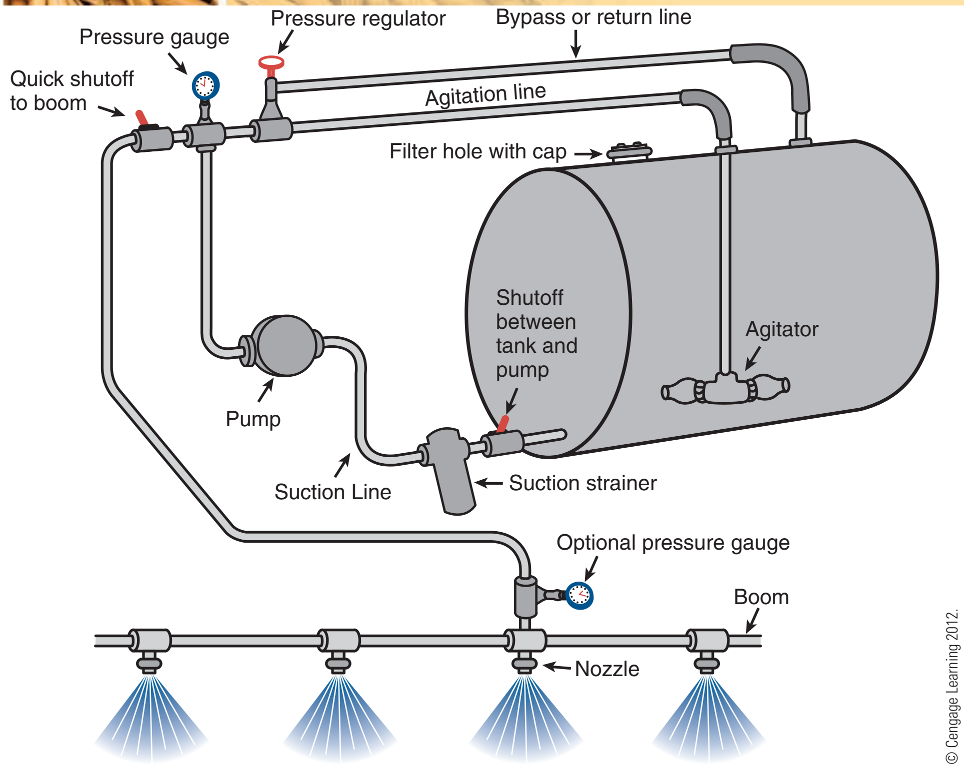


FIGURE 15-20
The important parts of an herbicide sprayer.



FIGURE 15-21
Field spraying of an herbicide.

species have developed herbicide resistance (Table 15-10). Herbicide resistance occurs because of repeated exposure of a population of weeds to a specific herbicide. As has occurred with antibiotic-resistant bacteria that affect humans, the few surviving resistant weeds go to seed, and the seed produces new generations of resistant weeds (Figure 15-23). Over time, all individual weed plants present in a field will have resistance to the herbicide.



FIGURE 15-22 Although ground spraying of herbicides is the most common approach, some herbicides are applied using aircraft.

TABLE 15-10

Some herbicide resistant weeds found in different regions of the United States. *Adapted from Heap (2010).*

Region	Weed	Herbicide resistance to:
North Central	Wild oats	diclofop-methyl
	Shattercane	primisulfuron-methyl
	Tall waterhemp	atrazine, glyphosate
Northeast	Lambsquarters	atrazine
	Redroot pigweed	atrazine
	Horseweed	paraquat, glyphosate
	Giant foxtail	foramsulfuron, imazamox, nicosulfuron
South	Palmer amaranth	imazapic, imazethapyr, glyphosate
	Smooth pigweed	atrazine, imazethapyr, nicosulfuron
	Barnyard grass	propanil
	Goosegrass	paraquat
West	Russian thistle	chlorsulfuron
	Redstem	bensulfuron-methyl
	Prickly lettuce	chlorsulfuron, imazethapyr
	Hairy fleabane	glyphosate, paraquat

Herbicide resistance develops because of inherent genetic differences in populations within a species. This genetic variation may create subtle differences in weed morphology such as an herbicide-resistant cuticle or hairiness that reduces uptake. Differences in biochemical pathways and herbicide translocation can affect or negate herbicide mode of action.

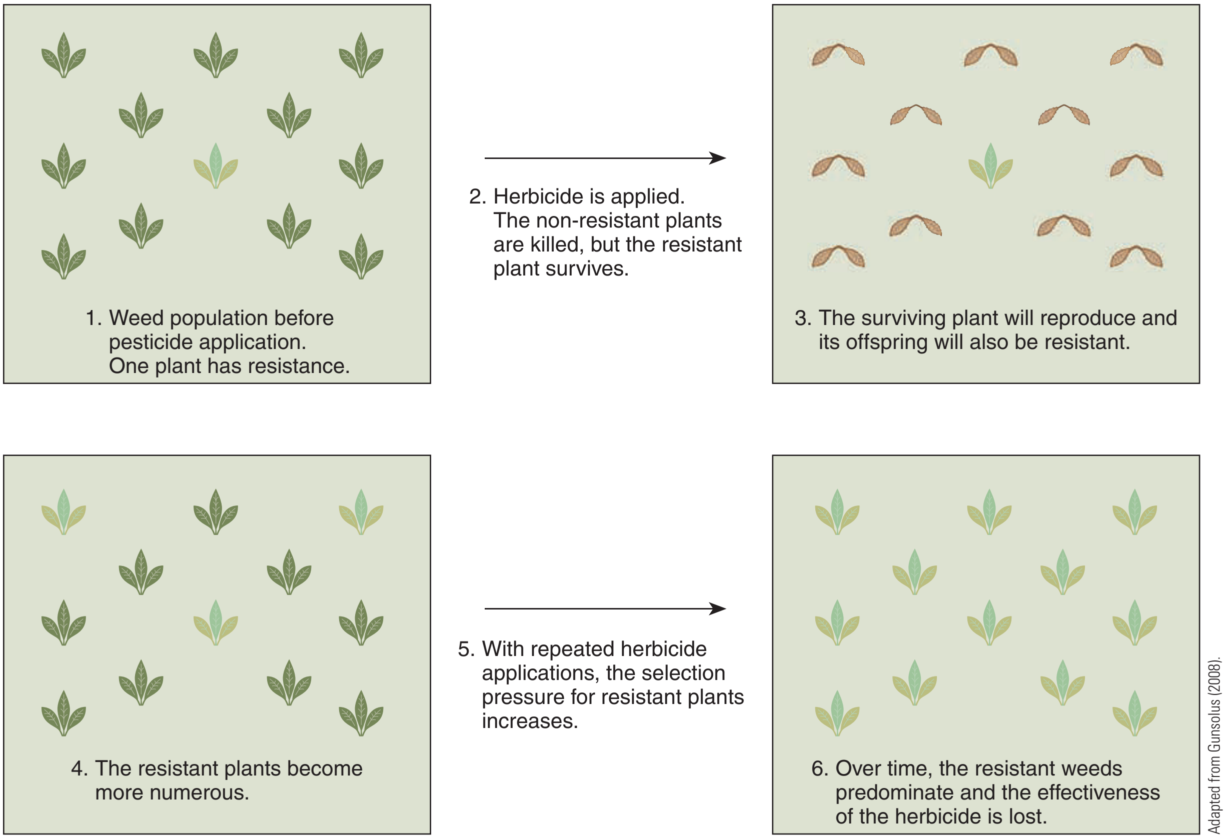


FIGURE 15-23 Steps in the development of herbicide resistance.

There are several steps to take to avoid herbicide resistance. These are to rotate herbicides over years and to use herbicides with different modes of action. A more traditional approach is to use alternative weed control strategies such as crop rotation and tillage. For more information on herbicide-resistant weeds in your area, go to http://www.weedscience.org.

Cultural Practices

In addition to herbicides, cultural practices such as crop rotation, biological control, and mechanical and manual control can be used to manage weeds.

Crop Rotation

Rotating crops in the same field over several years is an effective approach to weed control. Continuous and uniform cropping practices tend to select for weeds adapted to those systems (Table 15-11). Using a diversity of crop species increases the effectiveness of rotation. Following are some examples of cultural practices, including species selection, that affect weed control:

- **Corn vs. soybean.** Although both these crops are annual, the different heights result in selection for different groups of weeds. Soybeans shade the

Roundup-Resistant Weeds

Glyphosate (commonly known as *Roundup*) is a very effective chemical herbicide that is the most widely used herbicide in the United States. Roundup is a nonselective herbicide and, prior to the development of Roundup Ready crops, Roundup was used as a " burndown" or general application herbicide to control all weeds. Unlike many other commonly used herbicides, Roundup is relatively environmentally benign with a short half-life and low toxicity to humans, soil organisms, and other insects and animals. With the advent of Roundup Ready crops, weed control in agriculture was considerably simplified and practices such as no-tillage agriculture became possible on a wide scale. As a result, the adoption rate of and reliance on the Roundup Ready technology have been substantial (see Figure 15-16). The majority of corn, soybean, and cotton crops grown in the United States are glyphosate-tolerant.

Recently, weed scientists are finding evidence that the widespread use of this technology may be too much of a good thing. With glyphosate being common on multiple crops year after year, resistance to Roundup now has been found in 10 weeds in 22 states. Weeds that have been found to be resistant in the United States are johnsongrass, rigid ryegrass, Italian ryegrass, kochia, horseweed, hairy fleabane, giant ragweed, common ragweed, tall waterhemp, and Palmer amaranth (Heap, 2010). The southern part of the United States has been hit hardest, and the weeds in the Corn Belt are developing resistance rapidly. Resistance has also developed independently in Australia and countries in South America.

Researchers are seriously concerned over the increase and spread of Roundup-resistant weeds. The increased number of Roundup-resistant weeds may minimize the usefulness of the Roundup Ready trait in crops. This could potentially lead to farmers relying on more toxic herbicides, more frequent and labor-intensive management, and foregoing environmentally friendly farming practices such as no-till. It is anticipated that the use of other herbicides, including 2,4-D and dicamba (chemicals that are more toxic to the environment), will increase dramatically because of glyphosate resistance. Additionally, agricultural companies are in the process of developing crops resistant to dicamba and 2,4-D. However, if these crops become as widespread as Roundup Ready crops are, resistance to these herbicides will occur as well.

There are solutions to preserve glyphosate's effectiveness (or any herbicide's effectiveness) over the long term. Agricultural practices that avoid resistance need to be adopted by farmers and encouraged by the seed companies. Crop rotation with nonglyphosate-resistant varieties of crops may begin to address the growing weed resistance to glyphosate. Diversified weed-management techniques and varied selection pressures including utilizing a range of different chemicals, soil cultivation

practices and tillage, and utilizing cover crops—all can reduce reliance on a single chemical (and a single chemical pathway) for effective weed control. In addition, managing weed seed production and lowering the weed seedbank throughout the growing season will lessen the need for herbicides.

TABLE 15-11

Weed density by management, rotation, and crop in 1995 in Lamberton, MN. Conventional management used herbicides for weed control. Organic management used tillage for weed control. *Adapted from Porter et al. (2003).*

			Weed density in plants/m^2		Weed density in plants/ft^2	
Management	Rotation	Crop	Broadleaves	Grasses	Broadleaves	Grasses
Conventional	Corn-soybean-oat-alfalfa	Corn	2.6	67	0.2	6.2
Organic	Corn-soybean-oat-alfalfa	Corn	6.3	151	0.6	14.0
Organic	Corn-soybean-oat-alfalfa	Soybean	3.5	62	0.3	5.8
Conventional	Corn-soybean	Corn	2	322	0.2	29.9
Organic	Corn-soybean	Corn	6	517	0.6	48.0

soil faster in the spring following planting and are overall more competitive against weeds than corn. However, corn is more competitive than soybean with tall mature weeds such as velvetleaf. When herbicides are used in combination with crop rotations, broadleaf weeds are easier to control in corn than in soybean, and grassy weeds are easier to control in soybean.

- **Perennials vs. annuals.** Perennial crops such as alfalfa provide a tremendous advantage in controlling weeds compared to annuals like corn or soybean. In alfalfa systems with three or four harvests of the crop each season, flowering and reproduction of both annual and perennial weeds are eliminated or greatly reduced. Perennial weeds such as Canada thistle are killed because the removal of their herbage exhausts their root reserves. In contrast, some perennial weeds such as quackgrass can adapt to frequent cutting and are best controlled in annual row crops such as corn or soybean.
- **Plant population.** Increasing the population of some crops increases the speed at which the crop foliage covers the soil and shades weed seedlings.

- **Cover crops.** Some cover crops (see Chapter 13) can compete with weeds for light and moisture to suppress weeds. Winter rye grain is a widely used cover crop in the northern United States. It is typically planted following a corn crop in the fall and killed the following spring before planting the next crop, which is usually soybean. Rye is allelopathic and will kill or suppress weed seedlings that emerge.
- **Companion crops and intercropping.** Small-seeded legumes such as alfalfa are routinely established using companion crops such as oat or barley. The larger-seeded grasses form large plants quickly and compete with weeds as the weaker legume gets established. Small grains reduce weed yields but sometimes also reduce establishment of the legumes.
- **Planting date.** Planting dates can be altered to avoid times of greatest weed competition. Many weed seeds typically germinate in the early spring. Delaying planting until after the first weeds have germinated will allow a producer to control early-germinating weeds with preplant tillage or an herbicide. However, there may be a negative effect on crop yield with the shorter growing season.

Biological Weed Control

Biological weed control employs biological organisms (or agents) such as diseases, insects, or animals to reduce or eliminate populations of weed species. Biological agents control weeds in several ways: they consume foliage, they destroy roots and crowns, and they prevent flowering and reproduction. Prior to any introduction of a biological control agent, intensive testing is necessary to ensure that the agent is safe for the environment. There have been cases in the past where a biological control has affected nontarget species. The following are some examples of successful biological weed control:

- Purple loosestrife in North American wetlands. Weevils from Europe have been successfully introduced and have reduced or eliminated purple loosestrife by attacking different parts of the plant. *Galerucella pusilla* and *G. calmariensis* are leaf-eating beetles that feed on the leaves and new shoot growth. *Hylobius transversovittatus* is a root-boring weevil whose larvae feed on the root tissue. The flower-feeding weevil, *Nanophyes marmoratus*, reduces seed production.
- Leafy spurge in native rangeland and pastures in the northern Great Plains. An integrated pest-management approach (IPM) using a flea beetle, *Aphthona* spp. in combination with mowing and herbicides has been successful in reducing leafy spurge populations and their spread to new areas (Figure 15-24). Leafy spurge is unpalatable to cattle but is consumed by goats, sheep, and donkeys, which are used for its control in some areas.
- Prickly pear, introduced into Australia as an ornamental plant. In the early 1900s, it rendered nearly 100,000 acres (40,000 hectares) unusable for grazing. A moth borer (*Cactoblastis cactorum*) introduced from Argentina has controlled this invasive species.
- Canada thistle, an aggressive perennial weed of crops and pastures. A naturally occurring phytopathogenic bacterium, *Pseudomonas syringae* pv. *Tagetis*, has been shown to kill Canada thistle.



FIGURE 15-24
A flea beetle (*Aphthona flava*) feeding on leafy spurge. This insect is an example of a biological control agent.

Biological weed control has several advantages. It is a natural, nonpolluting approach to weed control that uses organisms that have been tested to be benign to other plant species. It can be targeted to a specific weed species. Some biological control organisms become established in the agroecosystem and can provide recurring weed control without reapplication of the biological organism.

Biological weed control is not without its challenges. Biological agents such as fungi and insects must be thoroughly evaluated for host specificity before release so that they do not attack desirable plants. The effects of biological control are often slow and may take several seasons as the control agent weakens the weed and prevents reproduction. Some biological agents may require specific climatic conditions for effectiveness; they can be effective in one environment but ineffective in others. Finally, biological agents can be relatively expensive to develop and apply.

Mechanical and Manual Weed Control

Mechanical and manual weed control are the most traditional approaches to weed control.

Manual labor is the earliest form of weed removal from crops. It has been practiced for centuries and is still used throughout the world. In the United States, high labor costs limit routine manual labor to high-value crops and to rescue situations. Manual labor can consist of hand-pulling of weeds or use of hoes and sickles.

Mechanical weed control is the use of tillage or mowing implements drawn by horses or tractors for weed control. It replaced manual labor for weed control in the United States. It is still used today, especially by organic farmers, who cannot use herbicides. Tillage controls weeds by uprooting or dismembering mature plants, burying germinated seedlings, burying seeds, or stimulating germination of dormant seeds or buds (Figure 15-25). Effective tillage must be timed to target weed growth at specific stages. It is very effective against small seedlings of both annual and perennial species, but less effective against annuals with large root systems, or perennials with methods of asexual reproduction such as rhizomes and stolons (see Figure 15-5).





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FIGURE 15-25
Weed control using tillage: in corn with a field cultivator (above) and in soybean using a rotary hoe (below).

TABLE 15-12

The total cost of weed control, the amount of yield lost if herbicides were not used, and the cost to replace herbicides with hand weeding and tillage by crop. *Adapted from Gianessi and Reigner (2006).*

	Total weed control cost ($ million/year)	Yield loss—no herbicides used (% of crop)	Herbicide replacement cost ($ million/year)
Corn	2600	20	5849
Soybean	2400	26	5082
Wheat	500	25	1176
Cotton	500	27	2290
Sugar beet	100	29	206
Rice	200	53	77
Canola	30	45	13
Potato	50	32	131
Sorghum	100	26	102

Tillage has some disadvantages that include the costs of machinery and its use, compaction of the soil by tractors, loss of soil organic matter and soil structure, and stimulating weed seeds that are present in the soils (Table 15-12). Tillage can also lead to an increase and spread in population of some species with rhizomes or stolons by cutting and moving these asexual reproduction structures. Tillage equipment is discussed in Chapter 14.

Mowing removes the aboveground shoot, leaves, and flowers of plants. Mowing after flowering is mostly an aesthetic activity because most weeds form seeds soon after flowering is initiated. Mowing can be accomplished manually using sickles or scythes or by using tractor-powered sickle bar mowers, disks, or flails. Mowing can kill many annual plants with limited root reserves, but some annuals can regrow from basal axillary buds. Repeated mowing can weaken perennial plants, but will often not kill them.

Weed Control Outcomes

In modern cropping systems, weed control is a never-ending battle. In response to a specific weed control approach, weed populations and species have been shown to adapt. Sometimes weeds of a specific species arise and are resistant to a control practice such as herbicides or mowing. Shifts in weed species can also occur. For example, if cultivation and herbicides are used to control broadleaf weeds, grassy weed problems can develop. It is vital to have an integrated approach to weed control, one that uses cultural, mechanical, and chemical forms of weed control.

Review Questions

1. Define the term *weed* and identify a weed that you know.
2. Why are weeds in crops a problem?
3. What are some traits of weeds that make them effective competitors with crops?
4. What is a noxious weed?
5. Describe at least three approaches to controlling weeds.
6. Why are herbicides the most common approach to weed control?
7. Are there any risks associated with herbicide use?
8. What is the purpose of an herbicide label? Describe essential components of an herbicide label.
9. Describe what is meant by the term *mode of action*.
10. When are herbicides applied?
11. What is an issue with the repeated application of the same herbicide to a specific field?
12. Why is crop rotation an effective weed control approach?
13. Describe biological weed control and give a successful example.
14. How does tillage work in controlling weeds?

Critical Thinking

1. Go to the website for the department of agriculture in your state and identify weeds that are considered noxious.
2. Some scientists, called *weed scientists*, study weeds and their control. From this chapter on weeds, identify an area of potential research for a weed scientist.
3. Herbicides are often maligned as a weed-control strategy. What would the consequences be if herbicides were eliminated and we depended on tillage or other approaches for weed control?
4. Go to a local store that sells herbicides. Select a product that is used for lawns, gardens, or field crops. Read the product's label and identify its name, active ingredients, target weeds and crop, classification, and precautions.
5. Is tillage always beneficial to the soil? Why or why not?

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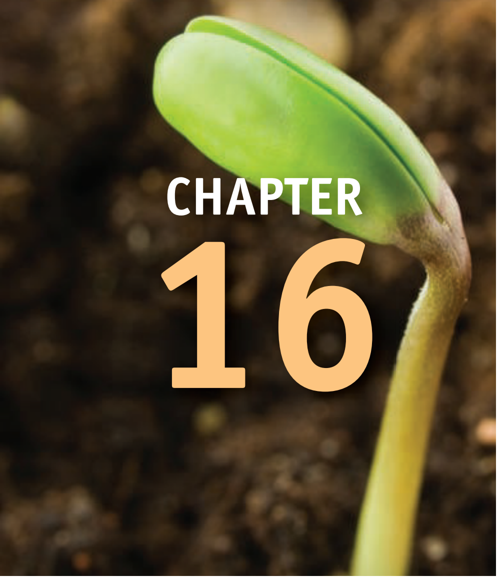
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CHAPTER 16



Plant Disease and Insects





Key Concepts

- Plant disease occurs when three factors are present: a pathogen, a susceptible host, and a favorable environment.
- Plant diseases are caused by either biotic organisms or abiotic factors.
- Biotic pathogens include fungi, bacteria, nematodes, mycoplasma-like organisms (phytoplasms), viruses, and parasitic flowering plants.
- Insects can damage crops in various ways in the field and in storage facilities.
- Some insects are considered beneficial as biological controls.
- Economic losses due to plant diseases and insect damage occur every year.
- Integrated pest management integrates multiple approaches to disease and insect control by using five basic strategies to achieve the desired pest control and still be cost-effective and environmentally friendly.
- Cultural pest management manipulates the crop environment and crop production practices to control pests.
- Biological pest management uses living organisms that prey, parasitize, or compete with pests to control the problem.
- Mechanical pest management uses equipment or other physical means to control pests.
- Genetic pest management uses plant breeding and genetic engineering to produce resistant cultivars to plant pests.
- Chemical pest management uses pesticides (organic, inorganic, natural, or synthetic) to control pests.

Key Terms

bacteria
biological pest management
chemical pest management
cultural pest management
disease triangle
fungi
genetic pest management
host
hot spot
integrated pest management (IPM)
mechanical pest management
metamorphosis
mycoplasma-like organisms (MLOs)
mycotoxin
nematodes

obligate parasite
parasitic flowering plant
pathogen
plant disease
saprophyte
symptom
virus

Introduction

Diseases and insects damage plants and have a detrimental impact on the profitability of crop production. Macro- and microorganisms—and sometimes specialized parasites—can cause plant diseases. Insects damage plants by consuming them and can also be vectors of plant diseases. By identifying the plant disease or insect pest, appropriate cost-effective and environmentally friendly management strategies can be implemented.

Plant Diseases

A **plant disease** is broadly defined as a progressive deviation from a plant's normal development, appearance, or function. The progressive nature of plant disease symptoms differentiates diseases from other types of injury. Plant diseases occur worldwide in many important crops and have significant, negative impacts on global food production and agricultural economies.

For a plant disease to occur, three factors must be present: a susceptible **host**, a **pathogen** (disease-causing agent), and a favorable environment for infection. These three factors form the **disease triangle** (Figure 16-1). A disease cycle is the series of events that occurs during the evolution of a disease. These events include infection and development of the pathogen, along with any changes or effects on the host. A **symptom** is the plant's response to the pathogen that we are able to see.

Biotic plant diseases are caused by living organisms such as fungi, bacteria, mycoplasma-like organisms, viruses, nematodes, and parasitic flowering plants.

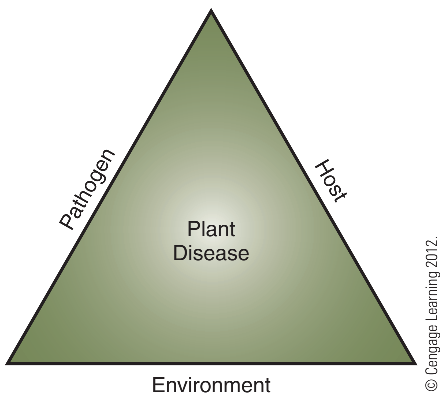


FIGURE 16-1
The disease triangle.

Plant diseases can also be caused by abiotic environmental factors such as air pollution, nutrient imbalances, water excesses or deprivation, extreme temperatures, soil acidity or alkalinity, and herbicides. To identify the pathogen and develop a method for disease management, it is important to determine the type of disease, biotic or abiotic, that is present.

Plant Pathogens

Plant pathogens are living organisms that cause biotic plant diseases. Generally, they are parasites and inflict damage to their host, causing symptoms that can be seen by the human eye. Some plant parasites are **obligate parasites**, that is, organisms that must obtain nutrition for survival from living host tissue. Obligate parasites cannot complete their life cycles without a host. If a host is not present, some of these organisms produce survival structures like spores, but others do not and will die. Other biotic plant pathogens can survive as either parasites or saprophytes. **Saprophytes** are organisms that use dead organic matter to obtain their nutrients when a susceptible host is not present or environmental conditions are unfavorable.

Fungi

Fungi are organisms composed of filamentous threads called hyphae that absorb nutrients. The hyphae grow and form a mycelium, a web-like mass that makes up the body of the fungus. Thousands of different fungal species can cause plant disease and there are many others that are nonpathogenic. Pathogenic fungi may be either saprophytes or parasites and may infect any part of a plant. Fungi reproduce via sexual and asexual spores. Spores vary widely in their forms, colors, and sizes, but all fungal spores have the same purpose: to ensure the survival of the fungus. Spores are dispersed in many ways including by wind, in water, in debris, and by insects or animals. Fungal spores can enter a plant by means of natural openings, injuries or wounds, or direct penetration through the epidermis. Some spores develop as survival structures when environmental conditions become hostile to the fungus. Some fungi have simple life cycles, but others can be complex and involve several spore types and more than one host to complete their life cycles.

Symptoms of fungal diseases vary according to the type of host plant and the plant part that is infected. Typical fungal disease symptoms include leaf spots (Figure 16-2), blights, wilts, rots, and cankers. Signs of fungal infections include mycelium, fruiting bodies such as mushrooms, survival structures, and spores.

Choosing the correct disease management strategy for a fungal disease depends on the fungal pathogen, the host or crop, and the environmental conditions. Most fungal diseases can be managed by using various strategies such as crop rotations, planting disease-free seed, removing plant debris (including alternate hosts or weeds), and chemical fungicides. Many important fungal diseases have significant yield and economic impacts around the world. Important fungal diseases include rusts, scabs, blasts, mildews, and smuts.

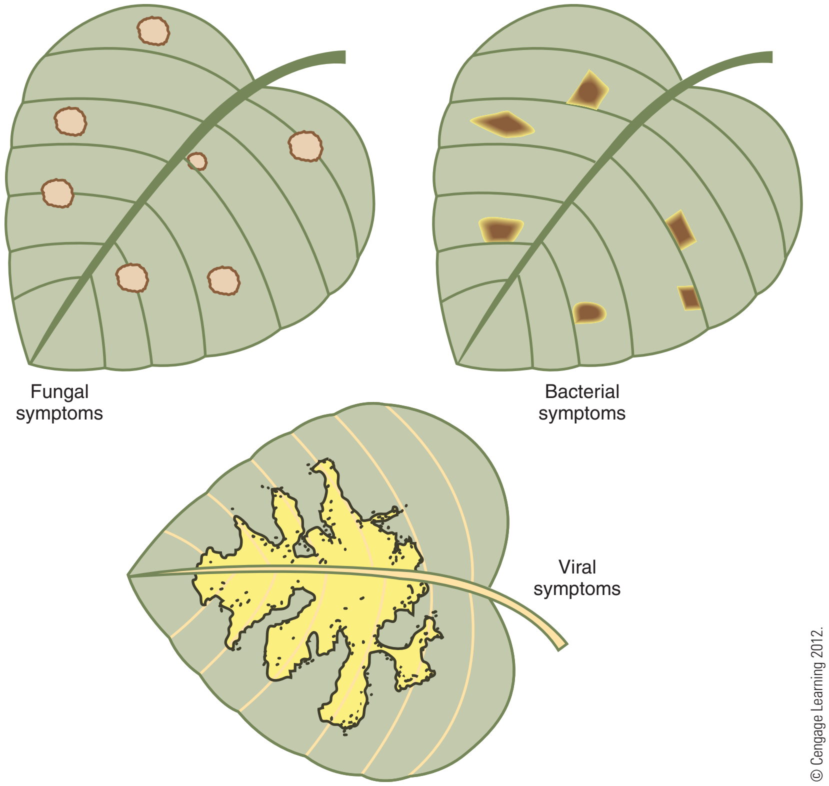


FIGURE 16-2
Fungal, bacterial, and viral leaf symptoms. Fungal mycelium form at the surface in round spots. Bacteria often form angular spots because they are initially limited by the leaf veins. One symptom of viruses can be a mosaic of yellow and green mottling. Another symptom is yellow leaf veins, which is called *vein clearing*.

Rusts

A group of fungi called basidiomycetes cause rust diseases, which are among the most important and destructive fungal diseases in the world. Rusts are especially devastating to small grains, but they also affect many other crops, vegetables, ornamentals, and trees. The rust fungi usually infect leaves and stems and appear as many rusty, orange, reddish-brown, or yellow spots. Each rust pathogen is a highly specialized parasite that infects only specific species. Stem rust (*Puccinia graminis*) of wheat and other grains infects all above ground parts of the plant (Figure 16-3). It reduces yield and quality of the grain. Stem rust has a complex life cycle requiring two alternate hosts and up to five different spore stages, both sexual and asexual (Figure 16-4). Rust diseases are easily disseminated by the wind, and in the United States, infected southern growing areas provide inoculum that is carried northward to initiate infections there. Asian soybean rust that reached the southern United States from South America via winds from a hurricane is now a threat to major northern soybean-growing regions in the Corn Belt. Rust diseases are most effectively managed by planting disease-resistant varieties.

Damping Off

Damping off is a disease caused by *Pythium* species that infects seeds and seedlings and, ultimately, kills them. In preemergence damping off, the infected seed or seedling dies before emerging from the soil. In postemergence damping off, the seedling has emerged from the soil, but it is infected on the stem at the soil line,



FIGURE 16-3
Wheat stem rust. The dark, flaking matter on the wheat stem is the rust.

where it will collapse and then die. Damping off has a wide host range and, because the fungus survives very well (not only in soils, but also in plant residue), producers should assume this pathogen is always present. *Pythium* prefers wet and cool soil conditions, and an effective method of disease management is to plant seeds or seedlings when environmental conditions favor them, not the fungus. Seed treatments also can be helpful to protect the seedlings during the early growth stages when they are most vulnerable.

Scab

Fusarium graminearum (the sexual stage is *Gibberella zeae*) causes fusarium head blight, a scab disease of wheat and barley. This fungus also causes stalk rot in corn. Symptoms of scab can be seen over the entire head (inflorescence) or on individual spikelets. At first, the spikelets may appear water-soaked and chlorotic (yellowing of plant tissue), but they change to a pinkish-red color. In wheat, portions or all of the head may appear bleached. Many infected wheat kernels are shriveled,

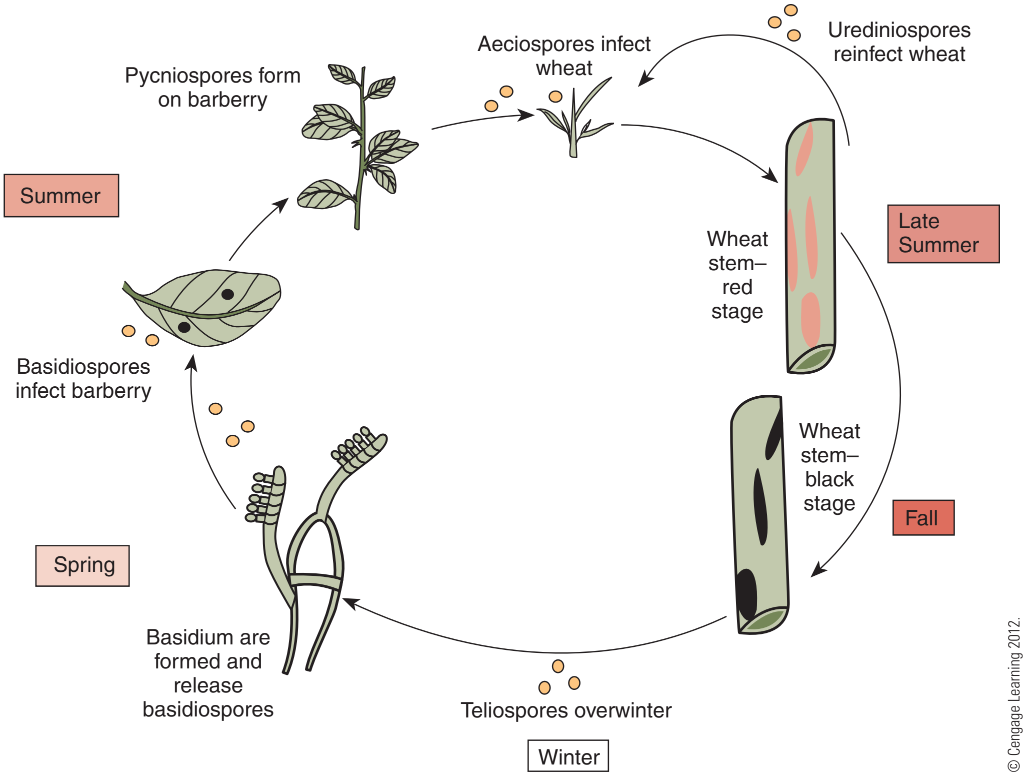


FIGURE 16-4 Simplified life cycle of stem rust. Spores are the reproductive (sexual or asexual) or survival phases of fungi. This fungus needs five spores (urediniospores, teliospores, basidiospores, pycniospores, and aeciospores) and two hosts (wheat and barberry) to complete the whole cycle.

lightweight, and appear gray or pink (Figure 16-5). These kernels are sometimes called *tombstones* because of their chalky appearance. Infected grain may contain fungus-produced toxic substances called *mycotoxins* (vomitoxin), which may cause vomiting in nonruminant animals and humans. Therefore, infected kernels are of limited value for some types of livestock feeding and are not used for human consumption. Scab can cause losses of up to 50 percent in yield. Scab is more severe in crops grown in areas that experience high relative humidity and high temperature during the heading and blossoming stages of the crop because these environmental conditions favor the fungus. It is a major reason for movement of wheat and barley production from more eastern states to dryland climates such as those found in North Dakota and Montana. Disease management of scab consists of growing resistant varieties, incorporating crop residues, managing soil pH, and lowering crop populations in the field. Excessive nitrogen fertilization should be avoided because it encourages the disease.

Ergot

Ergot is a disease of small grains, especially rye, and some grasses. It is caused by the fungus *Claviceps purpurea*, which infects the ovary of the host seed and replaces the kernel with a blackish, hard, survival structure called a *sclerotium*. *C.*

Ug99 Stem Rust: The Next Global Epidemic?

Stem rust has been a plague to wheat since its earliest cultivation. Stem rust infects stems as well as leaves with pustules that reduce yield or, in the worst cases, kill the plant. Modern plant breeders have successfully developed new varieties with resistance to the disease. For example, high-yielding, stem rust resistant wheat varieties developed by Norman Borlaug were the foundation for the "Green Revolution." Until recently, stem rust had not been a great problem for wheat growers. However, in the last 10 years, a new strain of stem rust has been discovered that threatens wheat-growing and barley-growing areas throughout the world. Called Ug99, the strain was named so because it was first found in Uganda in 1999.

Ug99 is such a concern because under the right conditions, Ug99 can cause complete yield loss. Most of the presently grown wheat varieties have little or no resistance. Because of the severity of the disease, 20 percent of the world's food supply could be threatened. As of 2010, Ug99 has been found in the following countries: Uganda, Kenya, Ethiopia, Sudan, Yemen, Iran, and most recently, South Africa. Farmers lost 80 percent of their crop in 2007 in Kenya, a country that can least afford any crop loss. While North America is geographically distant, stem rust has the capability of moving to new areas via jet streams. More unpredictably, humans could accidentally transport spores from infected countries. Scientists predict it is only a matter of time before Ug99 migrates to North America.

What can be done to prevent a worldwide stem rust epidemic? Scientists across the world are searching for new forms of resistance. One possible avenue of investigation is rice, which is not susceptible to Ug99, or wild varieties of wheat or its relatives. Scientists are also studying the fungus itself in hopes of finding weaknesses that can be exploited. A single resistant gene will not solve the problem. Numerous sources of resistance need to be found, because Ug99 can mutate readily. A number of promising resistant genes and breeding lines have been found by various researchers. These cultivars are already being tested in stricken areas.

purpurea produces small, fruiting bodies from sclerotia on the soil surface. These fruiting bodies forcibly expel spores into the air, where the spores land on the host's flowers and germinate, infecting the ovary and preventing kernel development. If they are ingested, ergot sclerotia are poisonous to animals and humans. During the Salem witch trials, ergot of rye caused the dementia that some associated with demonism. Management methods for ergot include the use of sclerotia-free seed lots, rotations to nonsusceptible crops, deep plowing of infected fields to bury the sclerotia and prevent germination of the fruiting bodies, and eradication of susceptible wild grasses (perennial hosts) in the area.



Keith Weller, USDA-ARS.



David L. Hansen, University of Minnesota.

FIGURE 16-5
Scab-infected wheat kernels versus healthy ones (above). A healthy head of wheat versus a scab-infected one (below).

Rice Blast

Blast disease, which is caused by *Pyricularia grisea*, is one of the most important rice diseases and occurs worldwide. The fungi overwinter in infected seed or in crop residue. Lesions from these fungi can affect the leaves, stems, or panicles. When the panicle stem of the plant is infected, kernel development can be impeded or prevented completely, depending on the stage of infection. During severe infestations, crop losses can approach 50–90 percent. Management methods include planting resistant cultivars, using minimal nitrogen fertilization, and fungicides.

Powdery Mildew

Powdery mildew is a very common disease found in a wide range of plants. It is an easily recognizable disease because of the white, powdery appearance of the fungus, which is usually seen on the upper surface of plant leaves, but may cover the entire plant. Powdery mildews are caused by *Erysiphe* species and are highly host specific. *E. graminis* infects cereals and grasses, whereas *E. polygoni* infects beans. Powdery mildews prefer environments that are high in humidity because they enable its spores to germinate. Powdery mildew also develops overwintering structures called *cleistothecia* that provide inoculum for the next year. Economic losses due to powdery mildew can vary depending on the crop and the amount of disease. In small grain crops where fungicide use may not be practical and debris removal is difficult, losses from this disease can be high. Powdery mildew control includes planting resistant varieties, fungicides, and avoiding excessive nitrogen fertilization.

Smuts

Smuts are named for the appearance of the black, powdery spores that the fungus produces. Smut fungi can infect many plant parts—including the grains or kernels—with these black spores. Smut disease symptoms include stunting of the plant and gall (plant tumor) formation. Corn smut (*Ustilago maydis*) can be seen as galls that typically form on the ears and tassels, but may appear on any above ground corn-plant part (Figure 16-6). For infection, this fungus prefers warm and dry



David L. Hansen, University of Minnesota.

FIGURE 16-6 Corn smut (*Ustilago maydis*).

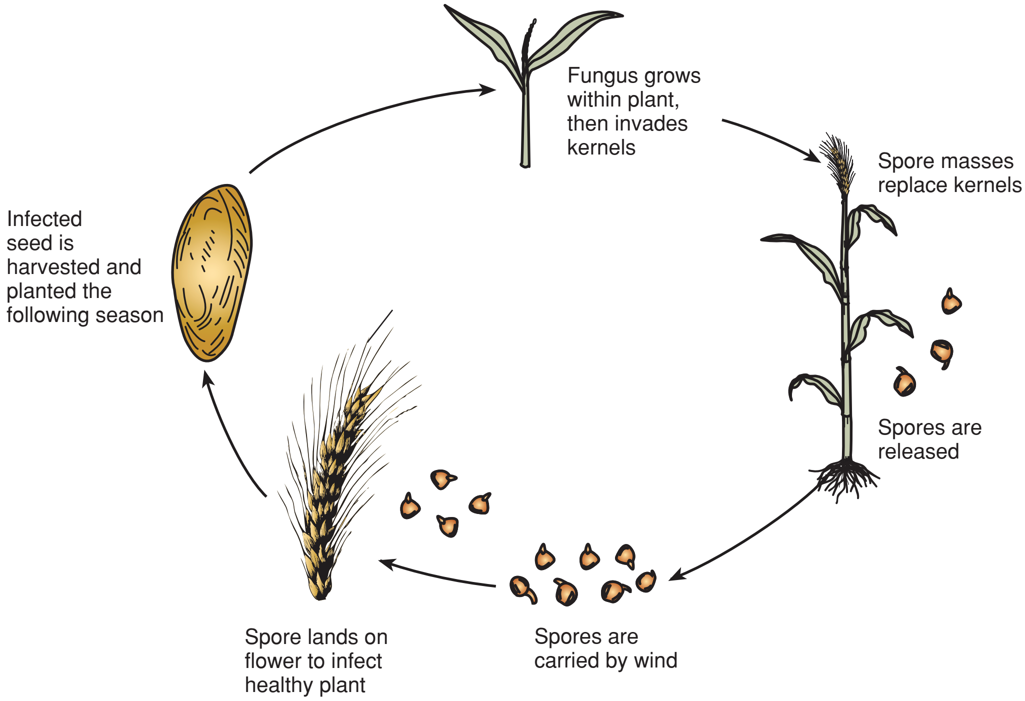


FIGURE 16-7 Disease cycle of loose smut (*Ustilago nuda*).

conditions and can survive not only in the soil, but also on plant debris. Removing any diseased material or debris aids in managing this disease. In loose smut of small grains (*Ustilago nuda*), the kernels/seeds are filled with black spores of the fungus. Infected seeds release the spores into the wind to spread the disease to other plants. Seeds also provide overwintering protection for the fungus. (Figure 16-7).

Postharvest Diseases

Most fungal pathogens that cause postharvest diseases are present in the crop before harvesting occurs, and the storage conditions can favor disease development. Some postharvest fungi such as *Aspergillus* species can produce chemicals called **mycotoxins** that even in low concentrations can be harmful to people and animals. Though most postharvest fungal diseases of consumable vegetables and fruits are easily visible as molds, contaminant on seeds or grains may not be as readily seen. If these seeds or grains are fed to livestock or ground for processed foods, they can cause health problems due to the presence of these mycotoxins. Postharvest diseases can be managed by maintaining cool storage temperatures, avoiding wounds or injuries, keeping humidity levels low to avoid excessive moisture, and applying chemical treatments to the harvested product.

Bacteria

Bacteria are microscopic, single-celled organisms. Most plant pathogenic bacteria are rod-shaped. Bacteria reproduce by fission, the process in which a single cell divides into two identical cells. Most plant pathogenic bacteria are present on plant surfaces,

where they survive on plant-cell exudates. When environmental conditions become favorable (i.e., warm and moist), the bacteria can become pathogenic to the host plant.

Symptoms of bacterial diseases are varied and may appear similar to those of fungal diseases. On foliage, bacteria can move between the cells of the host tissue and can cause angular, rather than spherical, leaf spots (see Figure 16-2). A leaf spot caused by bacteria may also have a water-soaked appearance or a border of chlorotic (yellowing) cells around the spot (a halo). Another common symptom of bacterial infection is wilting of the host plant. Wilts are caused by pathogenic bacteria that invade the vascular system of the host (xylem or phloem), clogging these vessels and inhibiting water and nutrient movement throughout the plant. Symptoms that the human eye can see include stunting, yellowing, or scorched-like appearance to leaves, and tissue deformities or growths. Soft rots are bacterial diseases that infect the fruit and other organs of a plant by breaking down the plant cell walls and causing them to collapse. This eventually leads to cell death.

Managing bacterial diseases is difficult and usually requires a combination of methods for any success. The first step is to plant only noninfected seed or disease-resistant varieties. Cultural practices such as crop rotation and the destruction of infected plant debris (sanitation) can help eliminate the pathogenic bacteria. Some common bacterial diseases include galls, wilts, blights, scab, and leaf spots.

Crown Gall

Crown gall is a widespread and economically important bacterial disease that affects more than 90 families of plants. It is caused by the bacterium *Agrobacterium tumefaciens*. Symptoms of this disease are the galls (growth malformations) that develop near the soil line on stems or roots. These galls first appear as small, soft, whitish, spherical growths that develop into large tumors with surfaces that are rough and dark brown in color. Effective treatments for crown gall are based on using good cultural practices such as planting disease-free or disease-resistant seed and properly cleaning and disinfecting tools and equipment. There are also root treatments available that use *Agrobacterium radiobacter*, an antagonistic strain of bacteria, to inhibit disease development.

Bacterial Wilt of Alfalfa

Bacterial wilt (*Corynebacterium insidiosum*) of alfalfa was a leading cause of stand failure before the development of resistant varieties. The soil-borne bacteria invade the plant through wounds on the roots or through stems that are cut during harvest. The bacteria then plug the vascular system of the plant. Affected plants are stunted and yellow. Susceptible alfalfa plants seldom live beyond two years after seeding. Most alfalfa varieties have been selected with resistance to this disease.

Bacterial Blights of Bean

Common blight (*Xanthomonas phaseoli*) and halo blight (*Pseudomonas syringae* pv. *phaseoli*) are bacterial diseases that have very similar symptoms in the field and are difficult to distinguish from one another. Symptoms of both appear on the leaves, stems, pods, and seeds of beans. The first symptoms are small, water-soaked spots that quickly enlarge, merge together, and eventually become necrotic (dead). Both bacteria can survive in infected seed and plant debris. Disease management of bacterial blights incorporates the use of disease-free seed, crop rotations, and, possibly, the use of antibiotics or chemicals.

Common Scab of Potato

Common scab of potato is a global bacterial disease caused by *Streptomyces scabies*. It generally reduces the quality of the crop, but not necessarily the quantity. The symptoms of common scab are seen as small, brownish blemishes on the surface of the tubers. These blemishes grow and become scabby in appearance. *S. scabies* can readily survive in plant debris and in soil. Infection occurs through wounds or natural openings on tubers, especially young tubers. Management strategies of this disease include using certified disease-free seed potatoes or disease-resistant varieties, seed treatments, and crop rotation.

Viruses

Viruses are extremely small, simple pathogens that are composed of nucleic acid (generally RNA for plant pathogenic viruses) enclosed in a protein case. They are obligate parasites requiring a host to survive and can only replicate within host cells. Almost 1000 species of plant viruses have been identified, and each species has specific strains.

Symptoms of virus diseases on plants can be distinctive, but others are easily confused with symptoms of other diseases. Common viral disease symptoms include stunting, tissue deformities, chlorosis, and vein clearing. Chlorotic areas may appear in easily recognizable forms such as rings or mosaics that are helpful in diagnosing diseases caused by viruses (see Figure 16-2). Virus symptoms are systemic in the host and are generally found in phloem tissue, which is how the virus moves within the plant. Viruses rarely kill their hosts because they require living host cells. However, they do reduce a plant's productivity and yield.

To move into a new host, viruses need wounds because they cannot move independently or penetrate a host by themselves. Most plant pathogenic viruses are spread by insect vectors or by contaminated equipment. Insects with piercing and sucking or chewing mouthparts can easily transmit viruses from one plant to another (Figure 16-8), but fungi and nematodes can also transmit viruses. Mechanical transmission of viruses occurs when infected sap from a diseased plant is transmitted to another plant that has been wounded by contaminated equipment.

Virus-infected plants cannot be cured, and no chemical controls are available to kill viruses. Most strategies for disease management rely on several factors including using virus-free seed, planting in virus-free or vector-free areas, removing infected plant material (including susceptible weeds), applying insecticides to remove insect vectors, using resistant plant varieties, and, if necessary, imposing quarantines. Some common virus diseases are mosaic viruses and dwarf viruses.

Tobacco Mosaic Virus

Tobacco mosaic virus (TMV) infects more than 150 genera of plants including tobacco, peppers, and other plants in the potato/nightshade family. It is found globally and causes significant yield losses. Symptoms include mosaic chlorosis, stunting, mottling, leaf curling, and possibly necrosis of plant tissues. TMV is a very stable virus and is easily transmitted to healthy plants by touch or rubbing it with contaminated equipment or hands. Disease management of TMV involves





FIGURE 16-8
The corn planthopper (*Peregrinus maidis*) (above) and the black-faced leafhopper (*Graminella nigrifrons*) (below). Both can transmit viruses to corn.

using good sanitation on equipment and hands, removing all infected material, and using resistant varieties of plants if available.

Barley Yellow Dwarf Virus (BYDV)

Barley yellow dwarf virus infects mostly small grain crops. Symptoms include stunting; yellow, orange-red, or purple leaf margins; reduced tillering (flowering stem production) and kernel filling; and sterility (Figure 16-9). BYDV is transmitted by aphids that acquire the virus through feeding on infected plants. The virus does not replicate in the aphids but can survive in them for days to weeks, thereby



FIGURE 16-9
Healthy wheat leaves (left) versus the bright yellow leaves (right) of wheat infected with barley yellow dwarf virus.

allowing the aphid to transmit the disease some distance away from the initial source. BYDV is effectively managed by using resistant varieties of plants and biological or chemical control of the aphid vectors.

Bean Common Mosaic Virus and Bean Yellow Mosaic Virus

Bean common mosaic virus and bean yellow mosaic virus can occur wherever beans are grown, but the bean yellow mosaic virus can also infect such plants as peas, clover, and squash. Generally, in bean fields, common mosaic virus is more widespread than yellow virus. Yield losses can be variable, up to 35 percent for common virus and up to 100 percent for yellow virus, depending on the plant growth stage when infected. Both diseases can be found in the same field and often in the same plants. Symptoms of both diseases include stunting as well as mottled and distorted leaves and pods. These similar symptoms make distinguishing between the two diseases in the field difficult. Both viruses overwinter either in seed or perennial hosts and are transmitted by aphids. To manage bean common mosaic virus disease, virus-free seed or resistant varieties should be grown. Bean yellow mosaic virus is harder to manage because there are fewer resistant plant varieties, but removal of susceptible perennial hosts, such as clover, helps reduce viral inoculum for the following season.

Mycoplasma-Like Organisms (Phytoplasmas)

Mycoplasma-like organisms (MLOs) (phytoplasmas) are microscopic organisms. They are similar to bacteria, having both RNA and DNA, but lack a true cell wall and cannot be grown in the laboratory on artificial growing media. Diseases caused by MLOs have been identified in field and vegetable crops as well as in fruit trees, where they can be very destructive. MLOs are found in the sap of the phloem and are transmitted from one plant to another by insects, commonly leafhoppers, grasshoppers, and possibly aphids. Symptoms of diseases caused by MLOs are systemic and may be rather difficult to distinguish, but can include a gradual

yellowing or reddening of the leaves, stunting of the plant, smaller leaves, and a general decline of the plant. Disease management strategies for MLOs include the use of insecticides to control insect vectors.

Aster Yellows Disease

MLOs cause aster yellows disease, which affects a large range of plant hosts including carrot, onion, tomato, potato, and barley. Symptoms of aster yellows disease are general chlorosis of the plant, stunting, abnormal growth of various plant parts, and an overall reduction of plant quality and yield. The disease overwinters in infected plants, and leafhoppers transmit it to healthy plants. Disease management strategies can be difficult, but eliminating perennial weed hosts and using a crop rotation with a nonsusceptible host helps reduce losses. Control of leafhoppers in the area also helps in reducing disease transmission to healthy plants.

Nematodes

Plant pathogenic **nematodes** are microscopic, nonsegmented, obligate parasitic roundworms that live mostly in soils, although a few species live on aboveground plant parts. Nematodes develop from eggs and grow through four juvenile stages before reaching maturity. Nematodes feed by using a stylet—a hollow, needle-like structure that penetrates into plant cells. Some nematodes are ectoparasites, that is, parasites that remain outside the plant tissue to feed. Others are endoparasites, that is, parasites that enter into the plant tissue to feed. A few ectoparasitic nematodes are capable of acquiring and transmitting plant viruses.

Host plant symptoms of nematode diseases include stunting, wilting, and chlorosis. In the soil, affected root systems show areas of necrotic lesions and root malformations. In fields with nematode infestations, symptomatic plants grow in circular, localized areas called **hot spots**. The presence of these hot spots is an important diagnostic tool for determining high nematode populations. Nematodes can survive in soil as eggs and do not produce any specialized structures. However, the eggs are vulnerable in adverse environmental conditions (i.e., winter or drought) and may die, causing natural population declines. Nematodes such as soybean cyst nematodes can also survive in cysts, in perennial plants, and in propagative parts of plants. Though some nematodes are migratory, they are able to travel only short distances through a thin water layer surrounding soil particles. To travel greater distances, nematodes require water (irrigation and rain) or soil movement by equipment and people.

Nematodes are naturally abundant in the environment, and no one, specific, management strategy can eliminate them. However, crop rotations and the use of resistant varieties can help manage problems. For high-value crops, soil fumigants can be used before planting to reduce nematode populations, and nonfumigant nematicides may be used after plant emergence. Plant pathologists are investigating methods of nematode control using fungi and other organisms that are predators or parasites of the nematodes.

Root-Knot Nematodes

Root-knot nematodes (*Meloidogyne* species) attack hundreds of plants and may be the most destructive nematode species globally in terms of crop losses. Aboveground symptoms of this disease include hot spots with plants that are stunted,

wilted, and deficient in nutrients. Below ground, the irregular knots (galls) are visible on the host's root system. In infected root and tuber crops, these plant organs will be deformed. Disease management methods for root-knot nematodes include using crop rotations with nonsusceptible hosts or resistant varieties.

Soybean Cyst Nematode

Soybean cyst nematodes (*Heterodera glycines*) are damaging endoparasites on soybeans and other legume crops. The host plant symptoms appear as a hot spot in the field with wilted and nutrient-deficient plants, but yield reductions may occur without obvious plant symptoms. There are three life stages: egg, juvenile, and adult (Figure 16-10). After hatching, the juveniles penetrate roots, which they then feed upon. Females' bodies swell as they become adults and form an egg-filled cyst. The cyst is visible to the naked eye and is an important diagnostic tool for this disease. Disease management strategies for soybean cyst nematodes include using crop rotations and resistant varieties.

Parasitic Flowering Plants

Parasitic flowering plants are obligate parasites that lack root systems and sometimes chlorophyll. They use haustoria (specialized roots) attached to their hosts to absorb water and nutrients. Though there are many parasitic flowering plants, only a few are of economic importance to crops. Symptoms of an infestation by a parasitic flowering plant include wilting, stunting, nutrient deficiencies, and abnormal growth. The parasitic plant survives by producing seeds that are dispersed to new areas. Disease-management methods for these parasitic plants include close inspection of seed lots and plant material for the presence of a living, parasitic flowering plant or its seeds, hand removal, herbicides, and planting of resistant or tolerant varieties.

Dodder

Dodder (*Cuscuta* species) is a yellowish vine that grows on the aboveground parts of its host, including alfalfa, potato, and many other plants. In addition to reducing yield, dodder can make harvesting difficult. Dodder produces seeds that survive in the soil (Figure 16-11). Management of dodder depends on the size of the infestation. If only a small area is affected, dodder can be removed before going to seed. If it is a large infestation, infested plants can be plowed under, or selective herbicides can be applied. Other economically important, plant-parasitic species include broomrape and witchweed.

Witchweed

Witchweed (*Striga* species) is a nonnative invasive plant that parasitizes grasses and grass crops such as corn, sorghum, rice, and sugarcane, reducing yield. It is a prolific seed producer, with one plant generating up to 50,000 seeds that can remain viable in the soil for up to 10 years. Witchweed was introduced to the southern United States sometime in the 1950s, but its spread was minimized by an aggressive eradication strategy. Witchweed is still an aggressive pest in many developing countries of Africa and Asia.



FIGURE 16-10
Soybean cyst nematode life cycle—nematode, cysts, and eggs. The front of the worm (top) is on the right, and the dark line visible at the end is its mouth and throat. The cysts (middle) are the dead (or soon to be dead), egg-filled bodies of the females. Cysts are visible to the naked eye and contain 200–400 eggs. The eggs (bottom) hatch when soil conditions are suitable.

Senyu Chen, University of Minnesota.

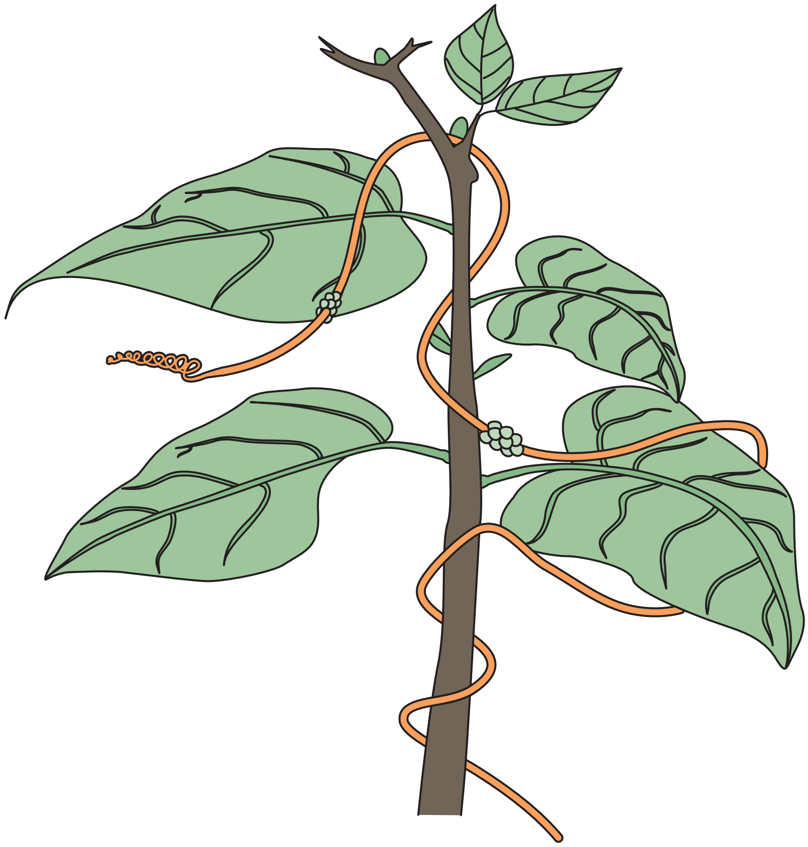


FIGURE 16-11
Dodder (*Cuscuta* sp.). The dodder plant is the string-like mass surrounding the stem and leaves of the other plant.

Insects

Insects are small, invertebrate creatures in the animal kingdom. They have six legs, a body with three main sections, and tough shell-like outer coverings. Mature insects have one or two pairs of wings and a pair of antennae. Insects make up more than 80 percent of all animal life and are widely adapted to most environments. They are economically important pests that cause direct damage to crop plants or are vectors of plant pathogens. Insects can be classified according to their life cycles or feeding habits.

Insects can reduce the leaf area of a plant by defoliation, leaf mining, and leaf curling. This decreases photosynthate (the end products of photosynthesis) normally available for plant growth and grain yield. Insects also cause damage by boring into stems and causing lodging. Chewing insects can also damage grain before harvest. Beneath the soil, root-feeding insects can injure or even kill plants by destroying root systems. In postharvest storage facilities, feeding insects can damage harvested crops.

Life Cycles of Insects

Every insect begins as an egg that may develop through several growth stages until maturing into an adult. ***Metamorphosis*** is a term used to describe these gradual developmental changes. The three classifications of metamorphosis used to describe insects are as follows (Figure 16-12).

- **No metamorphosis.** In this process, insects emerge from their eggs as miniature adults. Examples of insects with this type of metamorphosis are silverfish and springtails.
- **Incomplete metamorphosis.** In this process, nymphs emerge from eggs and gradually develop complete adult features and size. Examples of insects with this type of metamorphosis are aphids, leafhoppers, and grasshoppers.
- **Complete metamorphosis.** In this process, the insect has four separate life cycle stages: an egg, the larva, pupa, and adult. Examples of insects with this type of metamorphosis include butterflies, cutworms, and stem borers. The larval and adult stages of these insects are damaging to crops.

Because most insect pests are considered harmful only at certain stages, knowledge about an insect's developmental growth stages aids in determining the best control methods to use.

Feeding Habits of Insects

The types of mouthparts an insect has determine its feeding habits—either chewing or piercing and sucking (Figure 16-13).

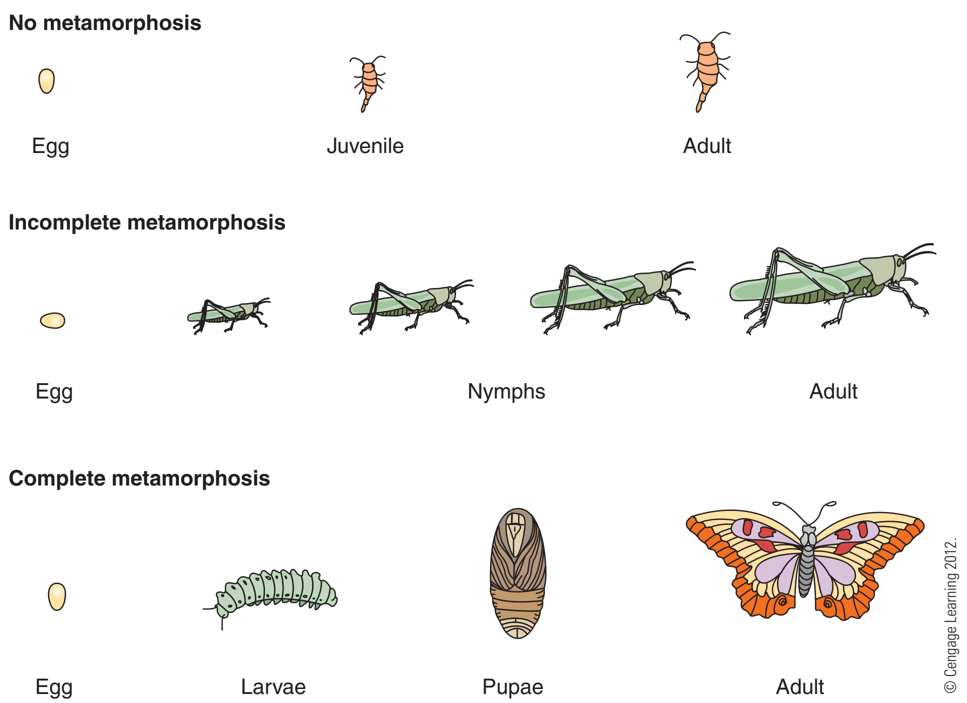


FIGURE 16-12
Three types of insect metamorphosis.

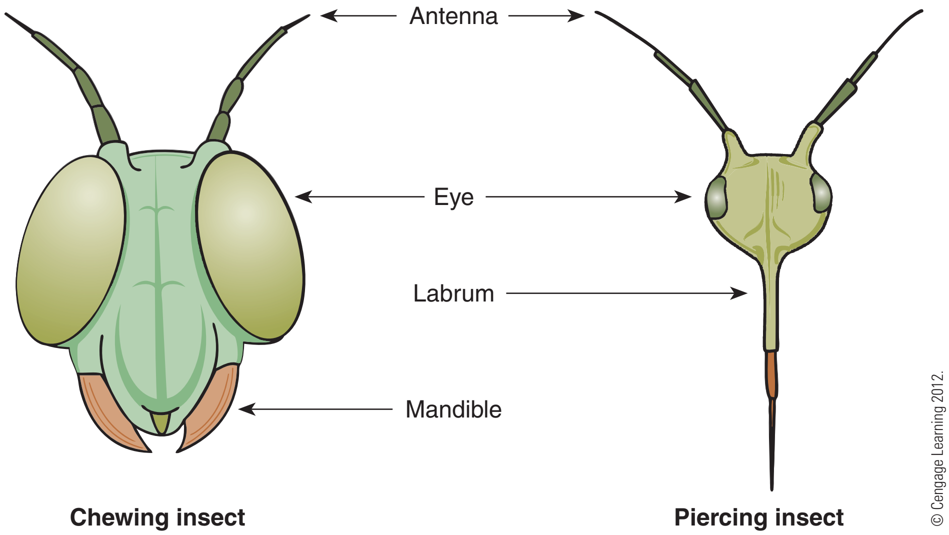


FIGURE 16-13
Insect mouthparts.

- **Chewing insects.** These insects have mandibles for chewing plant tissues while feeding. The damage from chewing insects can be readily seen as root damage, leaf mining, defoliation, and boring of tissues. Examples of chewing insects include caterpillar larvae, beetles, and grasshoppers.
- **Piercing and sucking insects.** This type of insect has a piercing mouthpart called a *labrum* that it uses to puncture plant tissue and suck the plant fluids. During feeding, these insects may cause additional damage because they can inject toxins or transmit plant pathogens such as viruses or bacteria into the plant. Examples of piercing and sucking insects include aphids and leafhoppers.

Important Insect Pests on Agronomic Crops

Around the world every year, many insect pests damage crops and, ultimately, yield. Some common, yet important, insect pests include the following:

Aphids

Aphids (Figure 16-14) are extremely common pests in both field and greenhouse situations. They reproduce many times in one year and can overwinter as eggs or adults. They have piercing and sucking mouthparts and are known vectors of plant pathogens, usually viruses. Ladybird beetles are natural predators of aphids, providing a biological control. High air temperatures also adversely affect aphid populations. Some important aphid species include the pea aphid (*Acrythosiphon pisum*), the soybean aphid (*Aphis glycines*), and the spotted alfalfa aphid (*Therioaphis maculata*).



Jim Kalisch, USDA-ARS.

FIGURE 16-14
Soybean aphid.

Potato Leaf Hopper

Potato leaf hoppers (*Empoasca fabae*) are an important pest of numerous crops. This tiny insect feeds on more than 100 plant species including soybean, potato, and peanut. However, it is particularly destructive to forage plants such as alfalfa and clovers. Leafhoppers have piercing and sucking mouthparts that remove sap from the plant and disrupt the phloem, resulting in shortened stem internodes and leaf yellowing. Insecticides are commonly used to control this pest.

Weevils

The alfalfa weevil (*Hypera postica*), both in its larval stage and as an adult, feeds on plant leaves. As an adult, the weevil overwinters in debris, and adults and larvae attack the first cutting of alfalfa. Insecticides are used to control the alfalfa weevil. Another notorious weevil is the cotton boll weevil (*Anthonomus grandis*), the most serious cotton pest in North America. Adults deposit eggs in cotton buds, and the larvae live within the cotton boll, destroying the seeds and surrounding fibers. The larvae of the boll weevil remain inside the cotton bolls and are difficult to kill.

Colorado Potato Beetle

The Colorado potato beetle (*Lepinotarsa decimilneata*) is a common pest on a variety of crops including potato and tomato. Both the larvae and adults feed on the foliage of the plants (Figure 16-15). Insecticides are a common control method of this pest.

Corn Ear Worm

Corn ear worm (*Heliothis zea*) larvae bore into the corn ear and feed on the developing kernels (Figure 16-16). Often fungi grow into infested ears as secondary invaders, causing further damage. Insecticides can be an effective preventive measure if applied before the larvae begin boring into the plant.



David L. Hansen, University of Minnesota.

FIGURE 16-15
Colorado potato beetle.



Jack Dykinga, USDA-ARS.

FIGURE 16-16
Corn ear worm.

European Corn Borer

Prior to the late 1990s, the European corn borer (*Pyrausta nubilalis*) was one of the most important insect pests on corn (Figure 16-17). The larvae bore into the corn stalks, causing lodging and ear drop before harvest. The insect overwinters in these lodged stalks and other corn debris and it can have multiple generations per season. Today, using resistant hybrids carrying the Bt gene can effectively control the European corn borer.

Grasshoppers

Historically, grasshoppers (*Melanoplus* species), also called *locusts*, may have caused greater crop loss than any other insect. Destruction of crops by grasshoppers has sometimes resulted in human famines. Grasshoppers will consume most



FIGURE 16-17
European corn borer. Adult moth and larva burrowing into stem.

cultivated crops and wild plants. More than 40 species of grasshoppers affect crop production in North America. Grasshoppers have chewing mouthparts that they use to feed on leaves and other plant tissue (Figure 16-18). Grasshoppers overwinter as eggs and emerge as nymphs. Spraying with insecticides when grasshoppers are in the nymph stage is the most effective method of control.

Beneficial Insects

Not all insects are pests. Many insects are beneficial because they are actually predators of other harmful crop insects. Predatory insects include ladybird beetles, green lacewing larvae, and parasites such as Ichneumon and Braconid wasps. Insects are also essential for pollination of some plants. Honeybees, alkali bees, and leaf cutter bees are used as pollinators in commercial seed production of alfalfa and other small-seeded legumes.



Jack Dykinga, USDA-ARS.

FIGURE 16-18
Grasshoppers feeding on crested wheatgrass.

Agricultural Pest Management Systems

There are several approaches to insect and disease pest management. In modern industrialized agriculture, farmers rely heavily on synthetic pesticides to control insect and disease pests. Some crops have also been genetically modified to be resistant to insect pests. In contrast, organic farmers depend on a few organic pesticides and cultural approaches. The most sustainable pest control practices use a combination of approaches.

Integrated Pest Management

Integrated pest management (IPM) is a strategy that acknowledges that plant pests are always present in the environment, and that the management objective is to keep the pest populations at levels that will not cause economic losses. IPM integrates a variety of management approaches to achieve the desired result and yet be cost-effective and environment-friendly. A sound, overall strategy is to grow healthy plants and to prevent pest problems before they occur by using proper tillage, planting good seed, using irrigation and fertilizers appropriately, and using clean, uncontaminated equipment. If a pest problem occurs, several important steps should be taken to develop a good IPM strategy. These include:

- Accurately identify the pest or problem.
- Evaluate the pest population and determine tolerable pest levels.
- Examine the economics and identify the best possible management method or combination of methods.
- Have a plan to monitor pests and to repeat any treatments if needed. Consider any environmental impacts the treatments may have.
- Be flexible if adjustments to the management strategy are necessary.

An IPM program uses five basic methods that can be applied to control a pest problem: cultural, biological, mechanical (physical), genetic, and chemical (Figure 16-19).

Cultural Pest Management

Cultural pest management attempts to manipulate the environment in which plants are grown. These management methods include:

- **Crop rotation.** Crop rotation is a planting system in which no single crop is grown in the same field year after year (see Chapter 13). This system prevents the buildup of disease pathogens and other soil-borne pests. Crop rotations

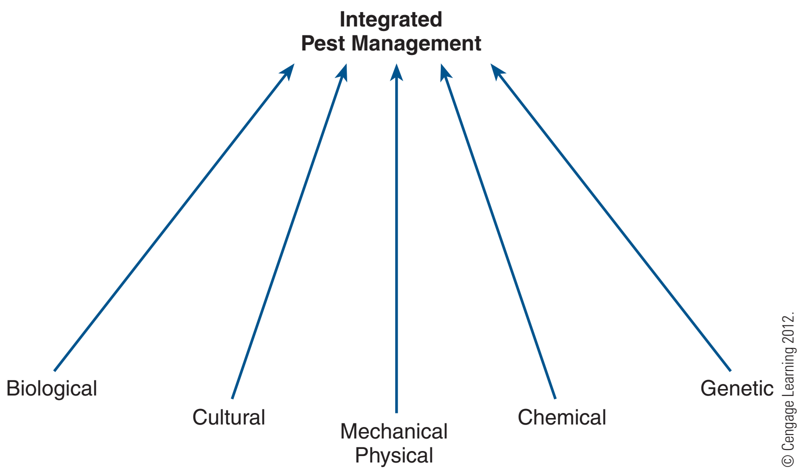


FIGURE 16-19 Five control methods used in integrated pest management systems.

must be diverse enough to have multiple years between crops with disease problems. For example, the corn-soybean rotation is not effective against the soybean cyst nematode because the nematode can survive for the year between soybean crops. A more desirable rotation would incorporate a small grain crop and one or more years of a forage legume such as alfalfa. As discussed in Chapter 13, the continuous corn-cropping system that has been proposed for use in ethanol production is very susceptible to the buildup of insect and disease pests.

- **Irrigation and fertilization.** These two management methods should be used to promote optimal plant growth and development. Crops that are well hydrated and have no nutrient deficiencies are better able to resist insect pests and disease pathogens.
- **Sanitation.** Good sanitation methods remove or incorporate crop residues that can harbor disease pathogens and insects. Good sanitation also means equipment and tools are properly cleaned or sterilized to avoid transferring contaminated soil or material to new areas. Destruction of crop residues using conventional tillage is controversial because of the value of residue for soil conservation.

Biological Pest Management

Biological pest management uses one living organism to control another by predation, parasitism, or competition. Biological pest management uses nature's own checks and balances system to prevent overpopulation of an organism. Because these management methods are biologically based, they are generally safer for the environment. Important biological pest management methods include the following:

- **Beneficial insects.** Beneficial insects are insects that prey on or parasitize other pests without harming the crop plant. Examples of these beneficial insects are ladybird beetles that prey on aphids, and a stingless wasp (*Microstomus aethipoides*) that parasitizes and destroys the alfalfa weevil.
- **Bacteria.** A bacterium, *Bacillus thuringiensis*, is a biological control used to kill various insect pests such as cutworms and corn borers. To provide this beneficial protection, the Bt gene has been isolated and genetically engineered into plants. Another bacterium, *Bacillus subtilis*, is used as a suspension treatment on fruits to delay brown rot, a postharvest disease caused by the fungus *Monilinia fruiticola*.
- **Green manures.** Green manures are crops that are grown to be plowed under to provide an environment that will increase soil populations of organisms that are antagonistic to plant pathogens.
- **Plant chemicals, toxins, or repellents.** Some plant extracts, such as nicotine from tobacco and pyrethrum from chrysanthemums, are naturally occurring chemical insecticides. Other plants produce toxins called *phytoallexins* when they are damaged or injured. These phytoallexins are poisonous to other competing or possibly infecting pests. Plant repellents are volatile scents that repel pests from a plant. Examples of plants that use repellents to control pests are marigolds, onions, and mint.

Biological Control of Soybean Aphid

Soybean aphid, a native of Asia, was first discovered in the United States in 2000. No one knows for certain exactly how the aphid was introduced. Unfortunately, once it arrived, it adapted quickly to infest all the soybean-growing regions. Its impact on soybean yield can be dramatic, with up to 50 percent reduction under heavy infestation, and growers have been forced to apply hundreds of millions of dollars' worth of insecticides to combat the aphid.

One possible control measure for soybean aphid, in addition to insecticides, may be the use of natural predators from the aphids' natural range in Asia. Scientists have surveyed predators of soybean aphid and found one promising species: *Binodoxys communis*, a parasitoid wasp (Figure 16-20). Research so far has progressed well. The wasp can reduce soybean aphid populations, and almost exclusively targets soybean aphid, rather than native species. In 2007, the USDA authorized experiments where the wasp is released onto farms in six states (Minnesota, Wisconsin, Iowa, Indiana, Michigan, and South Dakota). Part of developing a successful biological control is promoting self-sustaining populations of the predator. It will take many years before it is known whether *Binodoxys communis* will overwinter successfully and build up populations great enough to have an effect on the aphids. In the meantime, researchers are continuing to examine other possible biological control agents for soybean aphid.



David L. Hansen, University of Minnesota.

FIGURE 16-20 The oval, brown objects, called *mummies*, are a sign that the wasp has parasitized an aphid.

Mechanical Pest Management

Mechanical pest management systems attempt to manipulate the environment around the crop by using mechanical equipment or some other physical means to make it less favorable for the pest. Common mechanical pest management methods include:

- **Handpicking or trapping.** Handpicking is a labor-intensive mechanical management method in which the pests, such as beetles or caterpillars, are physically removed from the plants and destroyed. Handpicking can work well, but it is feasible only on a small scale for high-value crops. Setting traps for crop pests is another mechanical strategy that can also work well. Traps such as sticky paper strips that attract insects and adhere them to its surface work well for aphids and other smaller insects.
- **Tillage.** Plowing fields breaks up plant residue and incorporates it into the soil, where active soil microbes can degrade the debris. Today, minimum-till and no-till practices are increasingly used for reducing soil erosion and conserving soil moisture. Unfortunately, these tillage practices enable contaminated plant debris to remain on the soil surface, where the pathogens can overwinter and infect crops the following season. For example, head blight of wheat caused by *Fusarium graminearum* is a fungal disease that can become more devastating where reduced tillages are used.

Genetic Pest Management

Genetic pest management uses plant breeding and genetic engineering to develop plants that are more resistant to important plant pests (see Chapter 9). Plant breeding has provided many resistant cultivars, but it is a process that can take years to complete. Genetic engineering has also developed resistant cultivars in shorter periods of time. Bt corn is an example of a genetically engineered plant.

Chemical Pest Management

The idea of using chemicals to control plant diseases can be traced back thousands of years to 470 BCE, when Pliny wrote that an "amurca of olives" should be sprinkled on plants to prevent blight. In 1824, sulfur was recommended to control powdery mildews. In 1882, in Bordeaux, France, after the accidental discovery that a mixture of lime and copper prevented downy mildew, the first sprayed chemical, the Bordeaux mixture, was used to protect vineyards from that fungal disease. The development of synthetic organic fungicides and antibiotics for disease control started during World War II and continues today. Chemical pesticides can be extremely useful tools, but they must be applied with caution. A smart **chemical pest management** strategy first positively identifies the pest problem and seeks to understand the pest's life cycle so that the correct chemical and dosage will be applied at a time when the pest is most vulnerable.

A variety of chemicals are available to control plant diseases and insects: disinfectants, fungicides, nematicides, antibiotics or bactericides, and insecticides. Every year, millions of pounds of these chemicals are applied, and millions of dollars are spent to fight plant diseases in crops (Table 16-1). These chemical treatments may be applied in several ways: as seed coatings, as soil and foliar treatments, or

TABLE 16-1

Amounts and costs of insecticides, fungicides, and other pesticides in the United States, 2001. *Adapted from Kiely et al. (2004).*

	Amount of pesticide applied in million kilograms of active ingredient	Total cost in $
Insecticides	33	1,326,000,000
Fungicides	19	615,000,000
Nematicide/ fumigants/other	46	476,000,000

as fumigants. Chemicals are applied as a protective coating on crop seed prior to planting. Soil treatments are applied directly to the soil, where plants take up the chemicals through their root systems. Foliar treatments apply the chemical directly onto the foliage of the plant, where it is absorbed through stomata. Fumigants are chemical gas treatments applied before planting or after harvesting because they are often harmful to the plants themselves.

Like herbicides used for weed control, pesticides may cause environmental, animal, and health risks. They should be used according to label instructions.

Disinfectants

Disinfectants are used to clean and sterilize equipment and storage facilities. Disinfectants are relatively safe to use and they work well, but are not practical for many situations. Bleach (often a 10% solution), alcohol, and ammonia are common disinfectants.

Fungicides

A fungicide contains a chemical toxin that kills or prevents the development of a fungus. There are two general categories of fungicides: protectants and systemics. Protectant fungicides remain on the surface of plant tissues, creating a protective barrier. To provide long-term protection, these chemicals must be reapplied regularly. Systemic fungicides penetrate into plant tissue, where they kill or inhibit a fungus without damaging the plant itself. Pesticides have specific modes of action and resistance can develop with repeated applications.

Nematicides

Nematicides are used to reduce plant-pathogenic nematode populations. Nematicides are highly toxic chemicals that target nematodes' nervous systems, but they also harm any organism that has a nervous system, including humans. Great care must therefore be taken when applying these chemicals; their use is strictly regulated. It is possible that nematicide fumigants may be banned for any use in the future. Nematicides are expensive to apply and are generally used only on

high-value crops when nematode populations are extremely elevated and it may be cost-effective to use them.

Bactericides

Bactericides are used to control bacterial diseases. They are copper-based or use antibiotics in their formulations. Usually, very few antibiotics are used for controlling plant bacterial diseases because of their high cost and the risk of developing bacterial resistance. However, tetracycline and oxytetracycline are two antibiotics that have been used effectively to manage fire blight on some fruit trees. Copper-based bactericides are often labeled with copper-based fungicides and are used to control leaf diseases such as bacterial spot on tomatoes and peppers. These chemicals are protectants and will have no effect if infection has already occurred. They must be reapplied often, which can lead to the buildup of copper in the soil and copper toxicity in the plants.

Insecticides

Insecticides are chemicals that target and kill insects by various modes of action. They use inorganic or organic active ingredients. The use of insecticides as a management practice varies by crop (Figure 16-21). Inorganic insecticides use elements such as sulfur to control insect pests, but these are now used less because organic insecticides have become more popular and effective. Some organic insecticides are made from plant compounds that have natural insecticidal properties. Others, called *synthetic organic insecticides*, are artificially produced, but they are very effective on a wide variety of insects.

Insecticides can control insect pests in several ways including: systemic, stomach, or contact poisons; fumigants; and pheromones. Systemic insecticides can be applied as sprays to the foliage of a plant, or as a soil drench to be absorbed by the plant's roots. When an insect feeds on the treated plant, it ingests the poison, thus killing it. Stomach-poison insecticides are generally applied as foliar sprays. Like systemics, they must be ingested by the feeding insect, but they must be reapplied for continuous control. Contact insecticides must be applied so that contact is

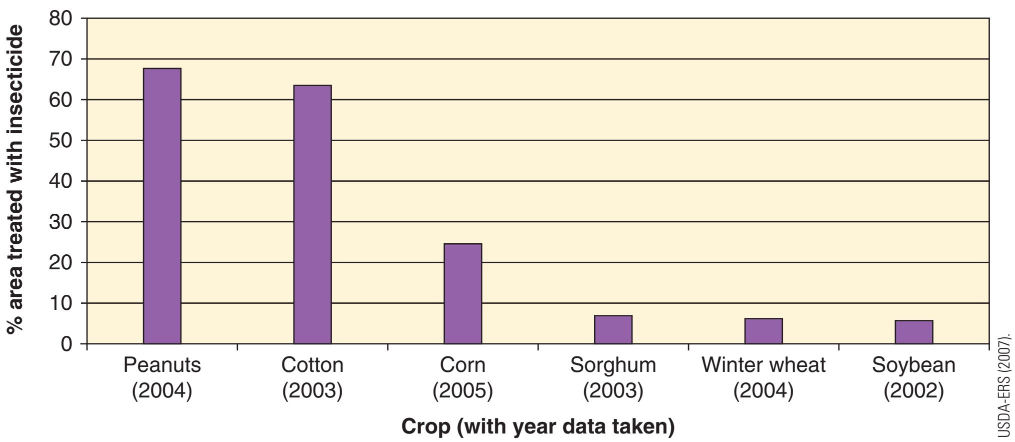


FIGURE 16-21 Percentage of total area treated with insecticide by crop.

made with the insect's exoskeleton. The poison is then absorbed into the insect's body, where it attacks the nervous and respiratory systems. If there is no physical contact between the insecticide and the exoskeleton, no control will occur. Insecticide fumigants are effective but dangerous chemicals because they attack the respiratory systems of insects as well as other organisms. Generally, insecticide fumigants are used in postharvest storage facilities and greenhouses. Pheromones are the chemical hormones released by female insects to attract males for reproduction. These chemicals have been identified and are used in traps that attract, capture, and kill male insects. Pheromones have been used to control such insects as the Japanese beetle and the cabbage looper moth.

Review Questions

1. What three factors need to be in place for a plant disease to occur?
2. What causes plant diseases?
3. Name some different biotic pathogens in plant diseases.
4. Are there specific parts of the plant that cannot be affected by plant diseases?
5. How do insects damage crops and reduce yields?
6. Describe how some insects can be beneficial as biological controls.
7. How does integrated pest management work?
8. Describe cultural pest management and how it works.
9. What is biological pest management?
10. What are some different mechanical pest management techniques?
11. What is genetic pest management?
12. Describe chemical pest management and the controversy that surrounds it.

Critical Thinking

1. For an important crop in your state, consult the library or a commodity-supported website (such as the American Soybean Association) and determine the important insects and diseases that can cause problems. What are the recommended control programs?
2. Select an insect or a disease pest and determine its origin and life cycle. How does it damage crops, and what is its economic impact?
3. Go to a local store that sells fungicides and insecticides for control of diseases or insect problems on a crop or ornamental plant. Carefully read the label for the product you selected and record the product brand name as well as its active ingredient.
4. Sometimes pesticides can leave residues on food products we eat. This occurs mostly on horticultural crops such as apples and celery. Does this concern you? How do state and federal governments insure food safety?
5. Consult the website for your state's department of agriculture. Outline the program for pesticide use regulation and pesticide applicator training.

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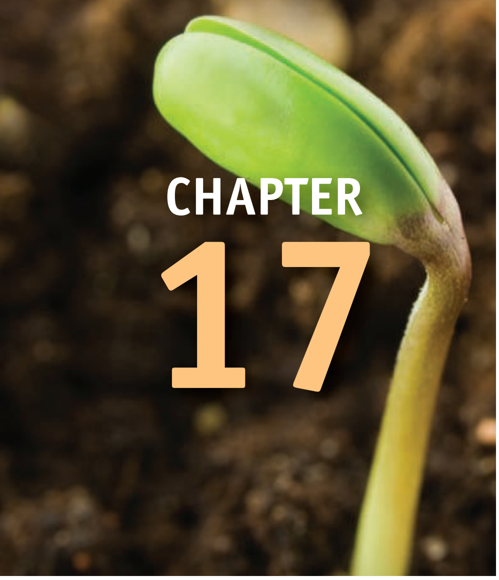
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CHAPTER 17



Harvesting





Key Concepts

- Harvest is the completion of the crop production cycle.
- The goal of harvest and storage systems is to maximize the harvest of the standing crop and preserve as much of the crop as possible.
- At physiological maturity, maximum accumulation of grain dry matter has occurred.
- Moisture level is a critical factor in preserving stored grain and forage.
- Forages are harvested directly by grazing or harvested as hay or silage.
- Approaches to grazing include continuous grazing and rotational grazing.
- Hay is stored aerobically, whereas silage is stored anaerobically.
- Hay often has significant field losses, whereas silage has greater storage losses.
- Types of silage include haylage, wilted silage, and direct cut.
- Corn silage is a high-energy feed stored at a moisture content of about 65 percent.
- Silage is stored in specialized structures, called *silos*, that exclude air.
- Grain crops, forage crops, cotton, tobacco, sugar beet, and potatoes require specialized harvesting equipment.

Key Terms

antiquality factor
binder
black layer
bushel
combine
continuous grazing
corn silage
direct cut silage
ensiling
forage quality
grazing land
harvest
harvest maturity
hay crop silage
haylage
husking
intake
lodging
milk line
nutritive value
pasture
physiological maturity
rangeland
reaper
rotational grazing
sheaves
shocks
shucking
stocking rate
storage fungi
stover
swathing
wilted silage

Introduction

Harvest of the crop is the completion of the production cycle and the end of a growing season. In early agricultural societies, survival through the winter was dependent on a successful harvest. If the harvest was plentiful, it would be a time for celebration and thanksgiving. Today, harvesting is the final step in providing commodities for marketing or for on-farm use. In modern production systems, harvest efficiency has been improved through mechanization, but successful harvesting is still influenced by the weather. In this chapter, we discuss the harvest and storage of important crops.

Harvesting Grain Crops

As discussed in Chapter 8, crops go through several stages of development until they reach the end of a growth cycle. For most annual grain crops, the growth cycle ends in seed production. This contrasts with forage crops such as alfalfa or grasses and corn silage, where harvesting for forage often occurs before seed production.

Bushels

Grain yield is typically measured in terms of bushel per acre. ***Bushel*** (abbreviated as bu.) is an old English term that describes a unit of volume for measuring crop yield. A bushel is a container 18.5 inches (47 centimeters) in diameter by 8 inches (20 centimeters) deep (Figure 17-1). Its volume is 2150 cubic inches (about 35,000 cubic centimeters). Today, the term *bushel* is still used to express grain crop yield, but for grain marketing, *bushel* is defined as the quantity of shelled grain at a specific moisture and specific weight. For example, a bushel of corn or grain sorghum weighs 56 pounds (25 kilograms) at 15.5 percent moisture; wheat weighs 60 pounds (27 kilograms) at 14 percent moisture; oats weigh 32 pounds (15 kilograms) at 14.5 percent moisture; and soybean weighs 60 pounds (27 kilograms) at 13 percent moisture. Other grains have specific bushel weights (see Appendix 3).

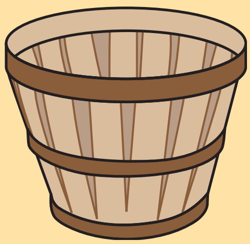


FIGURE 17-1 A bushel basket. Bushels are defined in terms of grain yield and marketing.

Profitable grain production must focus on maximizing grain yield and minimizing harvest and storage losses. This necessitates understanding the optimum maturity at which to harvest the crop.

Physiological Maturity of Grains

Physiological maturity is a stage of development of grains when the maximum accumulation of dry matter in the seed occurs. If grain is harvested before physiological maturity, grain yield is reduced. For corn, the average grain dry matter content increases about 2 percent per day from pollination to physiological maturity. Corn that is subject to frost or harvested before physiological maturity is called *soft corn* and will have lower grain yields. Physiological maturity can be determined by measuring the moisture content of the grain or by visual indicators. Grain moisture is an indication of crop maturity (Table 17-1 and Figure 17-2).

Visual indicators help determine physiological maturity. Several crops have simple visual indicators that can alert the farmer that physiological maturity is near. Some examples of visual indicators for corn, sorghum, soybean, small grains, and sunflower include the following:

- **Black layer in corn and sorghum.** In corn and sorghum, an abscission layer (a thin barrier of parenchyma cells) forms at the base of the kernel. This layer restricts translocation of carbohydrates to the seed. This layer is called the **black layer**. Corn grain moisture at physiological maturity is 30–35 percent.
- **Milk line in corn.** Another physiological indicator is the development of the **milk line** in corn. As the kernel approaches maturity, a line can be seen on the smooth side of the kernels. This line is called the *milk line* or *starch layer*. It is the boundary between the solid (starch) and liquid portions of the maturing endosperm. Physiological maturity of the kernel is indicated when the milk line is no longer visible, and liquid can no longer be expressed from the kernel.
- **Pod-color change in soybean.** The loss of green color of the pods is an indicator of physiological maturity in soybean seed. The pod contributes photosynthate (sugars from photosynthesis) to the developing seed. The change of pod color to yellow and brown is associated with seed drying and shrinkage.

TABLE 17-1

Percent moisture content at physiological maturity, harvest, market, and for safe storage. Long-term storage is for 1 year or more. These values are for the northern states; moisture values for safe storage in the South are lower.

Crop	Physiological maturity	Harvest	Market	Long-term storage
Corn	30–35	25	15.5	13
Wheat	30–35	15–18	14	13
Barley	30–40	10–18	13.4	12
Soybean	45–55	13	13	11

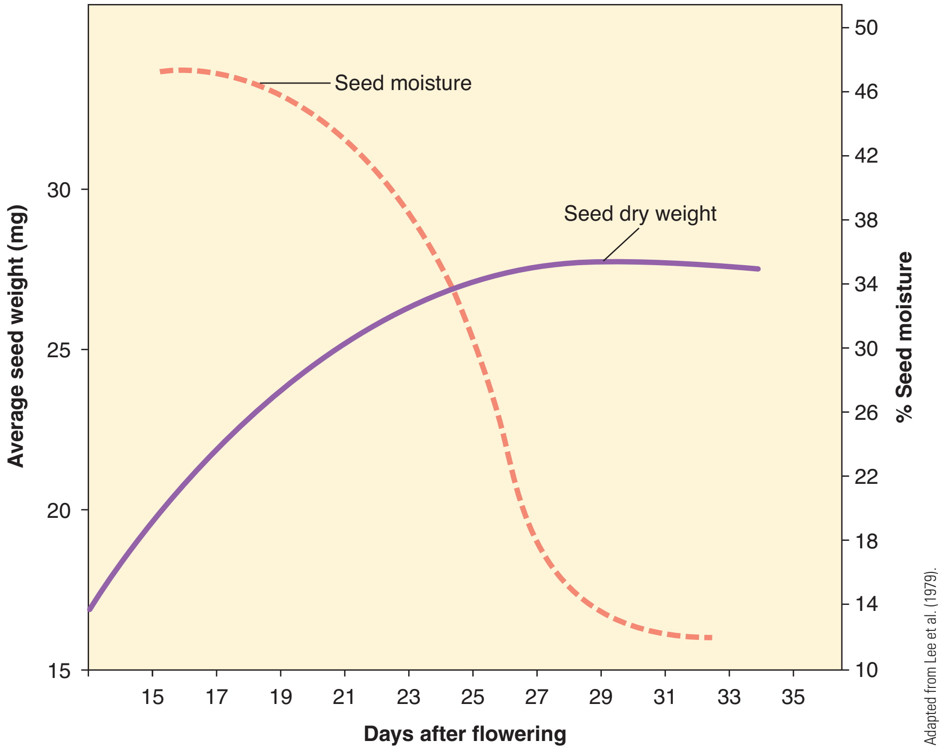


FIGURE 17-2
The relationship between oat seed weight and percentage moisture over time. Oat physiological maturity occurs at about 30 percent grain moisture.

- **Yellowing of small grain inflorescences.** A significant portion of the dry matter deposited in the grain of wheat, barley, rye, and oat comes from the awns, glumes, and other modified leaves in the inflorescence. Small grains are physiologically mature when these flower parts change color from green to yellow.
- **Sunflower head color.** Sunflower seeds are physiologically mature when the back of the head has lost its green color and turned yellow.

Drying of Grain before Harvest

Drying of grain in the field is a natural process designed to produce a seed that is less susceptible to attack by microorganisms and is more easily disseminated by the plant. Immediately following formation, the seed is almost 90 percent water. As the seed develops and accumulates nutrients, its moisture content decreases. After reaching physiological maturity, the seed continues to dry. At physiological maturity, grains are never dry enough for storage; therefore, considerable moisture loss must occur.

Water loss from drying grain occurs by whole plant transpiration and through direct evaporation from the grain surface. Water must move from the grain through seed coverings or husks. The drying rate of grain can be increased by those factors discussed in Chapter 8 that increase water loss from the plant. Increasing air temperature and airflow, and decreasing relative humidity, all increase water loss and the rate of plant and seed dry down. In contrast, as seed moisture decreases during dry down, the seed loses moisture more slowly. It should be noted that because of their starch content, seeds also absorb water from rain and snow.

Natural field drying is often the most economical approach to reducing the moisture content of seed.

Harvesting

The goal of harvesting is to maximize the removal of the agricultural crop from the field. This can be challenging because producers need to determine when to harvest, and because weather and soil conditions during the targeted harvest time can delay harvests. **Harvest maturity** is the moisture content of the crop when a combine can harvest grain with minimum field loss.

Corn is typically harvested when grain moisture levels reach 25 percent. The plant is brown or tan, but the leaves are retained. Harvesting at grain moisture levels greater than 25 percent results in grain losses because ears are not snapped off the plants as easily, and grain is not shelled off completely. At below recommended moisture levels, losses occur because the plant is more susceptible to lodging, ear drop, and seed shattering.

Soybeans are harvested directly from the field at a 13 percent grain moisture content to minimize field losses. At this time, the leaves have dropped from the plant and only a dried stem with pods remains. For soybean, harvesting losses of 10 percent or higher are not uncommon (Figure 17-3). Losses associated with harvesting are shattering of the beans and fallen stalks that cannot be picked up.

Small grains such as wheat, oats, barley, and rye can be allowed to dry standing in the field and combined directly or swathed before harvest. With **swathing**, the small grains are mowed, deposited on the ground, and dried in the field after they have reached physiological maturity. Swathing before harvest is an extra step, but is used if there is a variation in the maturity of the crops, or if a field has a significant weed problem. Immature weeds with high moisture content can block the threshing units of the combine. With cutting and drying in a swath, weeds can be fed through a combine and separated from the grain. In addition, swathing can reduce the risk of lodging of the mature crop, because the process dries crops to moisture levels safe for combining. **Lodging** occurs when the entire plant tips over. It can be a significant problem in high-yielding small grains.

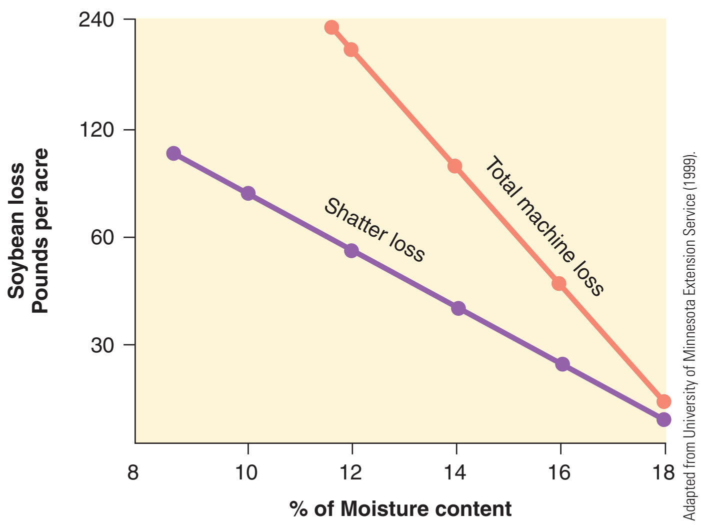


FIGURE 17-3 Soybean field losses associated with harvesting and shattering at several grain moisture levels. While losses are lower at higher moisture content, the optimum storage moisture for soybean is 13 percent or less. 1 pound per acre = 1.12 kilograms per hectare.

Method of Grain Harvest

All grain crops are harvested by combining. The term **combine** is used because this machinery combines many operations into one machine (Figure 17-4). At one time, the operations of cutting, gathering, and threshing (separating the grain from the chaff) were separate and very labor intensive. The combine cuts and gathers the crop, threshes (shells) the grain, and uses screens and fans to clean the grain. The grain is collected in a hopper in the combine and is later mechanically transferred to transport vehicles. Grain residue (straw, leaves, and stover) is discharged from the back of the combine (Figures 17-5, 17-6, and 17-7). The residue can be scattered or placed in rows (windrows) for later pick-up and baling.

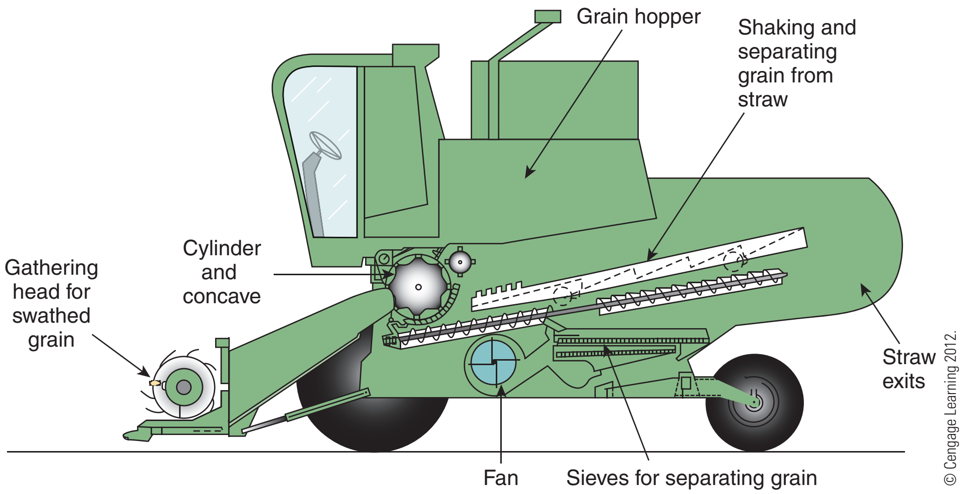


FIGURE 17-4 A self-propelled combine for small-grain harvest. The combine harvests, threshes, and separates grain from straw or stover. The gathering head brings the grain and straw into the combine; the cylinder and concaves thresh the grain; and the screens, fan, and straw walkers separate the grain from the straw. The straw is then expelled from the back of the combine.



FIGURE 17-5
A combine harvesting wheat. The combine cuts the grain, separates the seed and straw, and deposits the straw onto the field. The straw can be harvested and used for livestock bedding.



John Deere.

FIGURE 17-6
Harvesting soybean. Residue from soybean harvest is left on the field.



Dave Hein, USDA.

FIGURE 17-7
The combine has finished harvesting corn and is loading the grain into a trailer. The corn stover has been left on the field. It will be incorporated and provide organic matter to the soil.

Combines are complex and expensive machines. They require proper adjustment to minimize field losses and to optimize threshing efficiency. If the threshing is not adjusted, a significant amount of grain goes through the machine, or the grain can be damaged. Some farmers still use corn pickers that pick whole ears from the corn plant. These ears are often stored and fed to animals on the farm.

Drying of Grain for Storage

Several aspects of grain moisture are of concern.

- Grains are usually marketed at a certain bushel weight and moisture content. Grain that is marketed at moisture levels above the established limits are docked; that is, farmers receive less money per bushel.
- Grain moisture is a critical factor affecting storage. Seeds are living organisms and above-optimum storage moisture promotes seed respiration. Respiration reduces the seed's soluble carbohydrate content, releases moistures, and raises the grain's temperature. This can lead to fungi growth. Very high moisture levels and no aeration can actually lead to fermentation reactions within large storage bins.

Moisture content of grain crops at harvest is seldom at a level desirable for safe, long-term storage. The most traditional approach to reduce grain moisture level is to dry standing, unharvested crops in the field before storage. Field drying occurs by evaporation of moisture from kernels through corn husks, small grain glumes, or soybean pods. For corn and soybean, grain can lose as much as 1 percent moisture per day during good drying conditions.

Field drying of crops is a natural and low-energy approach to reducing moisture content, but there are risks associated with the process. Unwelcome wet and cool weather in the fall can delay harvest because moisture loss is increased by high temperature, sunshine, wind, and low humidity. Also, as the crops dry, there is often greater loss due to seed shattering, stalk lodging, and fungal growth on seed, especially with corn. Some fungi growing on corn while it is in the field such as *Gibberella* and *Fusarium* can produce toxins that are harmful to livestock and humans. Today, many high-value grain crops are harvested and artificially dried. Grains stored in piles or bins can be cooled and artificially dried using fans to move the air. Heated air can also be used to dry the grains. Alternatively, a combination of the two approaches can be used. Producers must pay for artificial drying (e.g., the costs for the propane and/or electricity, as well as labor costs) or allow for additional field drying. This decision is based on the cost of the energy source compared to market prices for the crop. Artificial drying can add as much as an extra 50 cents per bushel in production costs for a crop like corn, depending on the drying method and how wet the grain is.



Precision Agriculture

Precision agriculture is the use of computer-sensing and data collection equipment to enhance a farmer's decision-making capabilities. Whereas in earlier times farmers had to rely on whole field averages for chemical application, irrigation, and other inputs, today, the use of global positioning systems (GPS), geographic information systems (GIS), computers, and other sensing equipment allows for accurate, site-specific decisions. Here is how the various systems work.

- The GPS U.S. satellite navigation system uses signals from several satellites to locate the specific latitude and longitude of a position within a field. GPS enables farmers to divide their fields into smaller, digital subunits and collect data specific for those areas.
- GIS is a software system that stores, analyzes, and displays data that has been collected for a specific location identifiable using the GPS system. Data is often displayed in field maps.
- Data is collected from specific sites identified by GPS within a field. Data includes: soil characteristics based on manual soil sampling such as pH and fertility; crop yields and moisture content collected by yield mapping; other data such as presence of weeds and crop appearance. Data can also be collected by remote sensing devices mounted on harvesting equipment.

Within a field, there will always be a degree of natural variability in pH, soil composition, nutrient levels, soil moisture, and number of weeds that affect crop yield. With this data, farmers can accurately manage costly inputs on a spatial basis, thereby lowering their economic and environmental costs. For example, through the use of soil sampling equipment and the GIS system, farmers can create digital maps of their fields and determine which specific subunits need more or less fertilizer inputs. This process can save farmers money and enhance yields by accurately distributing resources to needy areas and reducing wasteful, average-based applications. Precision agriculture can also reduce farmers' environmental impact by minimizing and strategically focusing inputs and identifying areas in the farm landscape susceptible to increased runoff, water pollution, and contamination.

Yield monitoring using harvester-mounted computers and GPS systems has become commonplace for most crops (Figure 17-8). However, because of the cost, variable-rate application of crop inputs at specific sites within a field has been limited to high-value crops.



David L. Hansen, University of Minnesota.

FIGURE 17-8
A farmer using precision agriculture tools in the combine.

Grain Storage

Grain can be sold directly following harvest or stored on farm. Grain is stored if it is to be fed on farm or to create a marketing advantage for the producer. Storage seldom improves grain quality, but goals should include maintaining the quality (color, purity, odor) and viability if it is to be used for planting. Grain storage facilities vary considerably depending on the length of storage and the importance of minimizing losses (Figures 17-9 and 17-10).

Temperature during storage and length of storage time interact with moisture and can become a critical factor in determining storage losses. The minimum temperature for growth of storage fungi is about 40°F (4°C), with optimum



David L. Hansen, University of Minnesota.

FIGURE 17-9
A grain bin protects the grain from the weather and provides for aeration and long-term storage. Piles of corn (foreground) provide only temporary grain storage.



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FIGURE 17-10
Ears of corn stored in a corn crib. This corn will be used for feeding livestock.

temperatures from 80 to 90°F (27–32°C). Therefore, a strategy for reducing fungal growth is to store the grain at low temperatures. This often requires storage of grain in special grain bins with capacity for aeration.

Fungi, Insects, and Rodents

Damage from fungi is the most frequent cause of loss of grain quality and mass during storage. Losses increase as grain moisture levels increase. Mold growth can decrease seed viability and increase discoloration, changes in seed composition, dustiness, and production of toxic compounds called *mycotoxins*. The fungi responsible for the reduced quality of grain are called **storage fungi**. These include *Aspergillus* spp., *Penicillium* spp., and several types of yeast. The spores of these organisms are found on harvest and handling equipment. They are also usually present on the walls of storage bins.

Insects such as the granary weevil (*Sitophilus granaries*) and the saw-tooth grain beetle (*Oryzaephilus surinamensis*) can cause significant losses in stored crops. They consume stored seeds and also contaminate grains with insect fragments and feces. For food grains, they cause a major sanitation problem. Rodents can be a problem in unsealed storage containers.

Grain Harvest History: Bringing in the Sheaves

In the early days of agriculture, all crops were harvested by hand. For small grains such as wheat, farmers used the sickle, scythe, and cradle into the 1800s (see Chapter 1). The cut grain was later picked up by hand, loaded onto a wagon, and taken to a stationary thresher. Threshing was initially done manually but was later mechanized. During the early 1800s, manual harvesting was replaced by the **reaper**, a horse-drawn cutting machine that cut labor in half. The reaper deposited cut grain on the field, and then it was manually collected. The reaper was later modified to allow operators to collect and bind the stalks of grain together. Early **binders** depended on operators to use some of the straw for tying the grain bundle together. Later, as automatic binders were developed, the machines used wire and binder twine made of hemp fiber to tie bundles together. The binder was another technological revolution because tied bundles of grain (sheaves) were deposited in the field. These **sheaves** were stacked in the field to dry and were later transported to a stationary thresher that separated the grain from the chaff. By the mid-1850s, horse-pulled combines were available and were used on a limited basis.

Historically, corn was also manually harvested. Native Americans picked the ears of grain and left the stover (i.e., the remaining stalks, leaves, and husks) in the field for soil building. From colonial times into the 1800s, the corn stover was recognized as important winter livestock food and was removed from the field and stored. The grain was picked (called **husking** or **shucking**), and the remaining stover was then collected and tied into large bundles (**shocks**) of 10–20 plants to dry for livestock feeding. Another approach was to cut and shock whole plants in the field for drying. Then later in the field or barn, farmers husked the ears from the **stover** (the leaves and stalks of the corn; Figure 17-11). It took a farmer about a day to husk approximately an acre of corn that had already been shocked. As with small grains, inventors developed horse-drawn binders for collecting corn shocks. Later developments included corn-picking machinery that removed the whole corn ears and left the stover in the field. For many years, whole corn ears



FIGURE 17-11
A farmer husking corn from the stover. Whole corn plants are dried in the field in upright shocks.

were used for livestock feeding. Because of cost, shelling (separating grain from cobs) was limited. The first field combines that harvested and shelled corn grain were not developed until the early 1900s.

Harvesting Forages

Harvesting of forages occurs directly by grazing livestock or by mechanical removal as hay or silage (Figures 17-12 and 17-13). Forages are vegetative portions of plants used for livestock feed. Forages often do not contain mature seed. Corn, sorghum, and small grain crops harvested for silage contain immature grain. The goal of all types of forage harvesting is to maximize retention of the forage nutrients growing in the field. However, field losses as high as 25 percent frequently occur, especially for hay crops that are slowly dried in the field. Losses in crop yield and quality during harvest is greater for forages than for grains because fragile leaves often shatter or separate from the stem during drying and harvest of the forage. Shattered leaves are lost in the field.

Forage Yield

Forage yield is measured in tons per acre (or tonnes per hectare). Forages always contain some water, so hay yield is assumed to contain 15 percent or less moisture, whereas silage is assumed to contain about 60 percent moisture. Forage crops vary in yield potential (see Chapter 20) and yields are greatly affected by climate and soils. In humid regions, yields of fertilized cool-season grasses like smooth bromegrass average from 3–6 tons of forage per acre (7–13 tonnes/hectare) while in the south, Bermuda grass yields can average 8–10 tons per acre (18–22 tonnes/hectare). Corn silage yields can be as high as 30 tons/acre (67 tonnes/hectare). Forage yield is an important consideration for farmers, but forage quality is equally important.



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FIGURE 17-12 Beef cattle on rangeland in the western United States grazing native forages.



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FIGURE 17-13 Baling grass hay using a round baler. Hay is baled at about 20 percent moisture content.

Forage Quality

Forage feeding value is described as **forage quality**. The three components of forage quality are intake, nutritive value, and antiquality factors. **Intake** describes how much an animal will eat and **nutritive value** is the content of nutrients such as protein and energy. **Antiquality factors** include chemical toxins such as nitrates or alkaloids (see Chapter 15) that reduce forage palatability and livestock performance.

Description of forage quality is complicated because of the complex chemistry of forage cell walls (see Chapter 6). Whole plant forages contain greater quantities of cell wall structural materials such as cellulose, hemicellulose, and lignin than grains. Lignin is indigestible and interferes with the utilization of cellulose and hemicellulose, which contain the plant's energy. Forages also contain lower quantities of cell contents such as starch, protein, and organic acids. High cell wall content has been associated with reduced intake, digestibility, and nutrient content of forages. In contrast to grains, forage feeding value is much more variable. It varies among species and is greatly affected by factors such as maturity at harvest and growth conditions (Table 17-2).

TABLE 17-2

Nutritive values (crude protein, neutral detergent fiber, and digestible energy concentration) of some feeds. All data are on a dry matter basis. Neutral detergent fiber (NDF) represents the cell wall of the forage. More NDF results in less intake by livestock. 1 Mega calorie per kilogram = 0.45 Mega calorie per pound. *Board on Agriculture (2001).*

Feed	Digestible energy (Mcal/kg)	Crude protein %	Neutral detergent fiber %
Forages			
Barley silage	2.68	12.0	56.3
Corn silage	2.97	9.2	47.3
Grass hay (<20% legumes) mid-maturity	2.57	13.1	61.9
Grass silage (<20% legumes) mid-maturity	2.61	15.8	61.2
Grass-legume mixture, hay (40–60% legumes) mid-maturity	2.57	14.4	54.0
Grass-legume mixture, silage (40–60% legumes) mid-maturity	2.51	17.2	53.7
Legume hay (>80% legumes) mid-maturity	2.62	17.9	45.3
Legume hay (>80% legumes) vegetative	2.77	19.7	40.0
Legume silage (>80% legumes) mid-maturity	2.58	20.0	45.2
Legume silage (>80% legumes) vegetative	2.73	21.1	39.5
Sorghum silage	2.63	16.5	56.6
Concentrates			
Barley grain, rolled	3.64	12.4	20.8
Beet pulp, dried	3.03	10.0	45.8
Brewers grain	3.38	29.2	47.4
Corn grain, ground dry	3.85	9.4	9.5
Cotton seeds	3.55	23.5	50.3
Sorghum grain, dry rolled	2.83	11.6	10.9
Soybean meal	4.16	53.8	9.8
Soybean seeds, whole roasted	4.72	43.0	22.1
Sunflower meal	2.90	28.4	40.3

When to Harvest

Maturity of the forage crop at harvest affects both yield and quality. As the forage crop matures from vegetative (all leaves) to flowering, forage yield increases, but forage quality decreases. This is related to the decrease in leafiness with maturity and the increased proportion of the fibrous stem. For mature plants, the lower leaves on stems may actually senesce or fall off.

Producers use indicators of grass and legume development in order to determine when to harvest their crops. General stages of development of a forage legume such as alfalfa and red clover are as follows (Figures 17-14 and 17-15) (see Chapter 8):

- **Vegetative:** stems have leaves but no buds or flowers.
- **Bud:** stems possess flower buds but not showy flowers.
- **First flower:** first flowers are present.
- **Flowering:** multiple flowers are present.
- **Seed/Post-flowering:** green and mature pods contain seeds. Plants may still have some flowers present on the stem.

Some stages of development for a forage grass such as smooth bromegrass and orchard grass are:

- **Vegetative:** plant has only leaves but no stem development.
- **Stem elongation:** stems have elongated but no inflorescence is showing.
- **Boot stage:** inflorescence is enclosed in the sheath of the flag leaf.

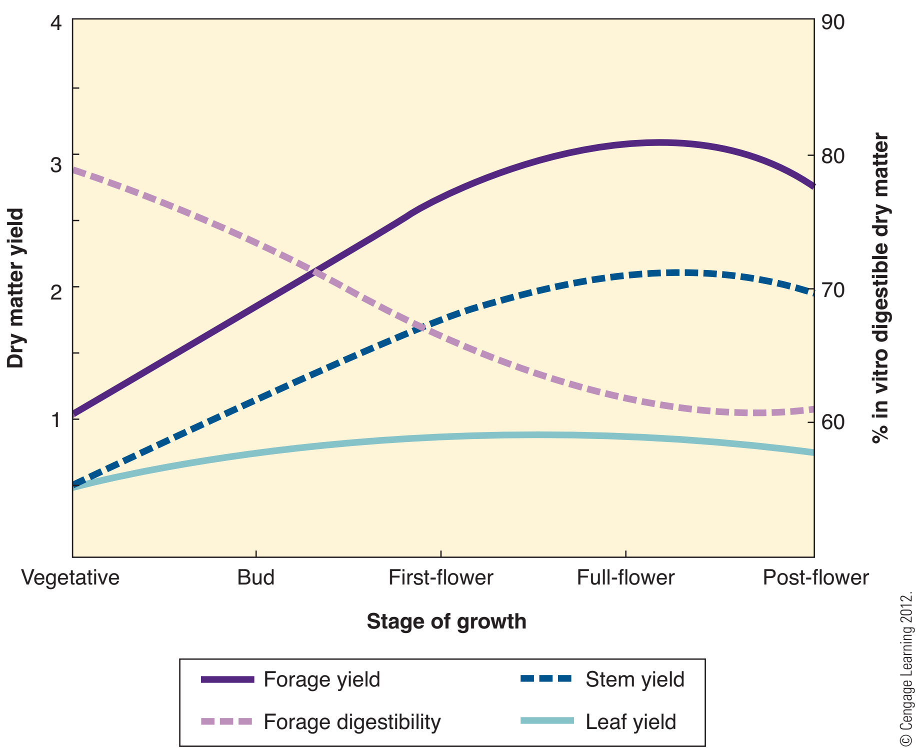


FIGURE 17-14 The effect of alfalfa maturity from vegetative to flowering stages on forage yield and forage digestibility. With increased maturity, yield increases as nutrient concentration decreases. The stem yields increase with maturity while the leaf yields decrease.



FIGURE 17-15
A mature stem of alfalfa has more stems and less leaves than less mature alfalfa.

- **Flowering/anthesis:** grass anthers are shedding pollen and fertilization is occurring.
- **Milk stage:** the seed is formed but immature milk-colored juice can be expressed if the seed is squeezed.
- **Dough stage:** the seed is formed but the endosperm is somewhat soft if the seed is squeezed.
- **Ripe seed:** mature seed is present and seed coatings are brown.

Grazing

Grazing lands are agricultural lands with plant herbage that is suitable for grazing livestock. Two types of grazing lands include pasture and rangeland. A **pasture** is grazed land on which annual and perennial forages are grown. The predominant plants used for pasture vary throughout the United States. These include perennial grasses such as Kentucky bluegrass, smooth bromegrass, orchard grass, ryegrass, and legumes such as alfalfa and white clover in the humid northern region; tall fescue, bahiagrass, and Bermuda grass in the south. In pasture systems, animals spend up to three-quarters of each day grazing. On well-maintained pastures, grazing animals can obtain almost all their nutrient needs.

In humid regions, grazing of pastures is less important than stored feed on many modern beef and dairy operations. The extensive use of stored hay and silage

has become commonplace to minimize animal movement on the farm and to achieve a more reliable and consistent-quality forage. Animal diets are supplemented with high-energy grains.

Grazing of forages is the direct utilization of plant materials by foraging cattle, sheep, bison, and horses. Grazing or pasturing is limited mostly to the portion of the year when the plants on pastures or rangelands are actively growing or are not covered by snow. There are different types of grazing systems including continuous grazing and rotational grazing.

Continuous grazing. Animals have access to a large pasture, and they move freely about the grazing area. This approach is common in grazing of expansive rangelands in the western United States where productivity is limited by lack of rainfall, or in regions where soil fertility limits grass productivity. Continuous grazing is a low-input management system compared to rotational grazing. Continuously grazed pastures typically undergo seasonal cycles of overgrazing and undergrazing depending on the weather conditions.

Rangeland is a type of grazing land that includes native species such as switchgrass, little bluestem, and buffalo grass and is more common in the drier western region. Rangeland can consist of hundreds of plant species, while pastures have only a few species or can even be a monoculture of a single species. Unlike pastures, rangeland is usually not fertilized.

Rotational grazing. In contrast to continuous grazing, rotational grazing involves dividing the pasture into three or more paddocks. With rotational grazing, animal grazing is controlled and pasture plants can be provided a rest period that increases plant persistence. Forage is used more efficiently than in continuous grazing systems because animals are managed to utilize forages when they are at optimum nutrient levels for a specific type of livestock (Figure 17-16). In rotational grazing systems with cool season forages, grazing is usually initiated when plants are vegetative and pastures are grazed to a height of 3 inches (4.5 centimeters) within 1 week at a maximum. For cool season forages in the northern United States, the average rotation period is about 30 days, but is more frequent in the spring when grass is actively growing and less frequent when grass growth is slowed in summer. For switchgrass in Nebraska, it is recommended that grazing begin when plants reach a height of 10 inches (25 centimeters) and cease at a stubble height of 6 inches (15 centimeters). Plants need to be rested 30–45 days before being grazed again.

Managed intensive grazing is another rotational grazing approach in which cattle are managed to maximize pasture utilization. Cattle are provided new pasture as frequently as every 12 hours (Figure 17-17). Other managed intensive grazing includes strip grazing and creep grazing. In strip grazing, portable fencing is moved daily to provide a fresh supply of forage. Creep grazing is a modified rotational grazing approach that gives calves access to the highest quality forage because they graze ahead of the cows.

There is growing interest in the use of rotational grazing in production of "grass-fed beef" and "grass-fed dairy" enterprises. These practices that rely heavily on nutrients grazed from pasture are designed to produce healthy meats and milk in a natural way. Several studies have shown that meat from grass-fed livestock often has less fat and higher concentrations of beneficial omega-3 fatty acids and conjugated linolenic acid than meat from animals fed grain diets (Karsten and Baer, 2009).

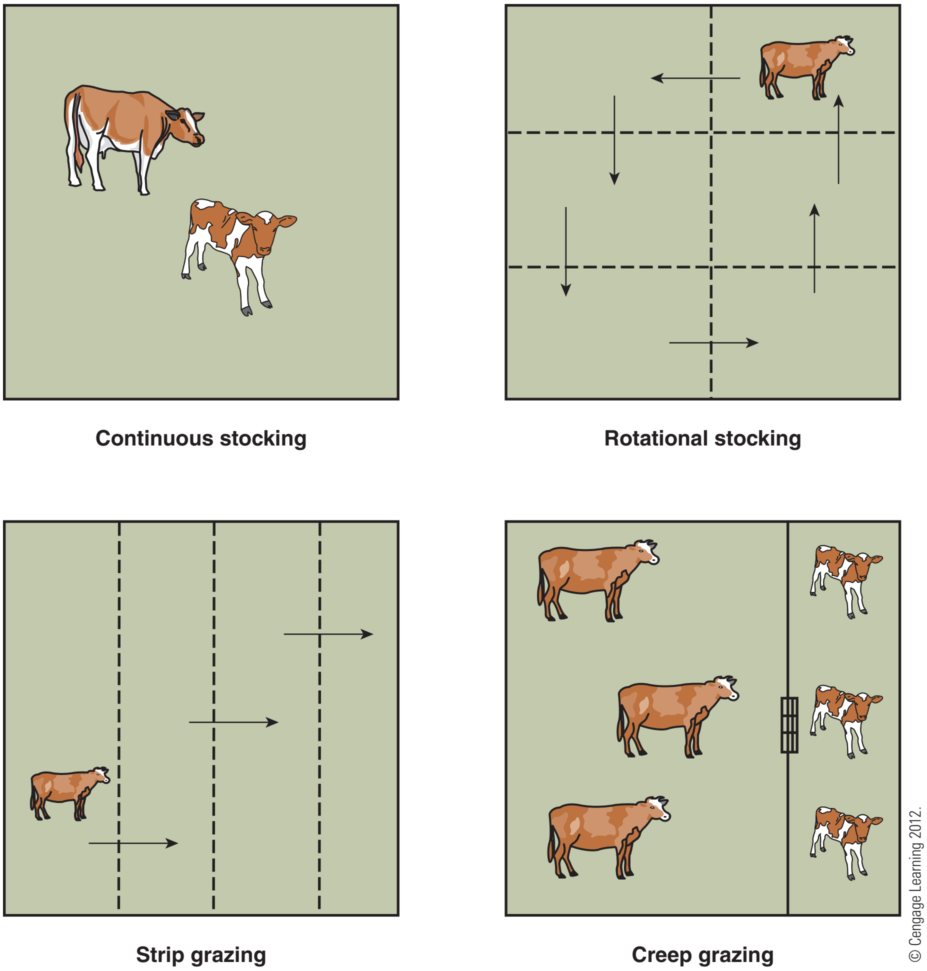


FIGURE 17-16 Alternative grazing strategies. With rotational grazing, strip grazing, or creep grazing, animal access to the pasture is controlled, which results in better use of the pasture. Rotational grazing provides for better pasture utilization than continuous grazing.



FIGURE 17-17 Dairy cattle grazing perennial grass pastures in southeast Minnesota. This rotational grazing system is called *management intensive* grazing. Cattle are moved to new pasture every 12 hours and grazing is controlled using electric fencing.

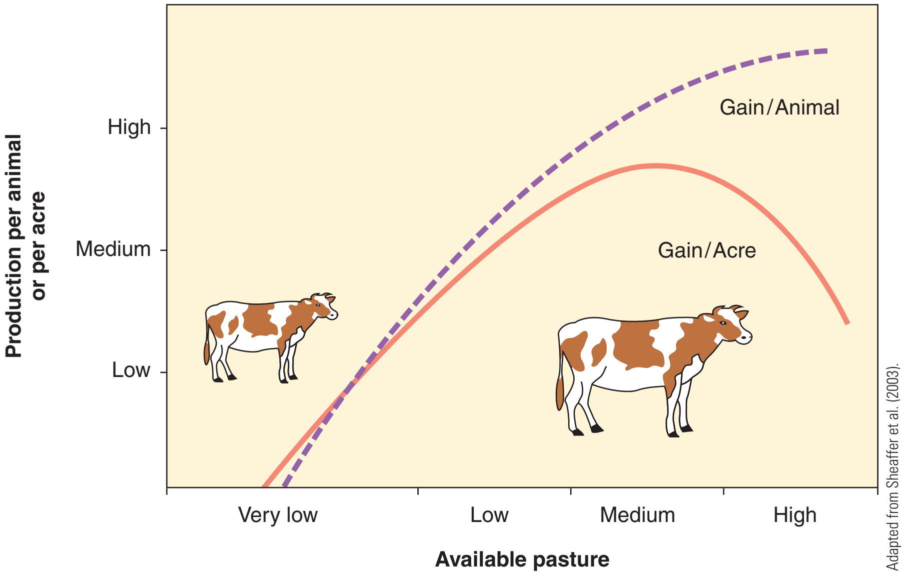


FIGURE 17-18
The relationship between available pasture and relative production per animal and per acre. As pasture availability increases, performance per head increases because animals can select the highest quality forage. However, gain or production per acre decreases at high levels of available pasture because of incomplete consumption of the available forage.

Stocking Rate

Animal performance on pastures is greatly influenced by **stocking rate** (animal number per acre). At low stocking rates such as those often used for horses, animals can select forage with higher forage quality (Figure 17-18). Unfortunately, animals often select and overgraze the most palatable species. As the stocking rate increases, selectivity is decreased. However, the total weight gain of the livestock in the herd increases until there is too little forage to support the animals in the herd. This often happens when there are droughts in midsummer or in the late fall when climatic conditions reduce plant growth.

Haymaking

When pasturing is not possible, haymaking is the traditional approach to harvesting and storing forage for livestock. With haymaking, farmers typically schedule multiple harvests during the growing season. At each harvest, forage is removed and herbage regrowth occurs. Alfalfa is the leading hay crop in the United States, but many other perennial legumes such as red clover and grasses like timothy, Bermuda grass, and smooth bromegrass can also be made into hay. Hay is forage that is dried to about 15–20 percent moisture and stored aerobically (in the air). Hay that is stored above 20 percent moisture content can mold, which leads to heating and a loss of forage mass and forage quality. Overall, because of multiple operations and dependence on the weather, haymaking is risky. Field dry matter losses of 25 percent are not uncommon (see Figure 17-21). Additional losses occur during storage. In the haymaking process, there are four critical steps—cutting, drying, packaging, and storage.

Cutting

The standing plants (containing about 80–90% moisture) are cut leaving 1–3 inches (2.5–8 centimeters) of stubble near the ground. It is deposited in windrows, which are rows of cut forage fluffed to increase wind flow (Figure 17-19). Most modern mowing machines have a conditioning unit that crushes the stem of forages and aids drying.



FIGURE 17-19
Windrows of alfalfa deposited with hay cutting equipment. The windrows are so named because they catch the wind and aid drying. Standing forage contains from 80 percent to 90 percent moisture and must be dried to less than 20 percent moisture for safe, long-term storage. Field drying normally takes from 2 to 4 days depending on the weather.

Drying

The cut forage is dried in the field about 1 to 4 days depending on the temperature and sunshine. For example, in the Midwest, hay can dry in 2 days in mid-summer, but in the fall drying may take 4 days. During this time, the hay is sometimes raked or turned over using equipment called *tedders*. The expression *making hay while the sun shines* is based on the common practice of using the sun's energy to dehydrate the forage. Rain during hay drying is undesirable because it prolongs the drying process, causes leaf loss, and leaches valuable nutrients. Sometimes the entire hay crop can be lost if rain falls about for several days following cutting. An inch (2.5 centimeters) of rain that falls on nearly dried alfalfa hay can result in a loss of 50 percent of the leaves that are the most nutritious part of the forage.

Packaging

Historically, hay was removed from the field in a long, loose form that often involved significant manual labor (see Figure 1-18). Today the dried forage is compressed and packaged in the field using hay balers that are pulled behind and powered by tractors. Baler components include pick-up fingers to lift the dried hay into a bale chamber that compresses the hay. Bales are then wrapped with netting or twine. The size and type of bales vary depending on the feed market. Bales can be small, rectangular packages weighing about 50–70 pounds (23–32 kilograms), large, rectangular packages weighing about 500–2000 pounds (230–910 kilograms), or large, round packages weighing as much as 500–2000 pounds (Figure 17-20). Larger hay packages are made faster and are moved mechanically. Smaller hay packages are more suited to manual handling.

Transport and Storage

The baled hay is transported from the field using wagons or trucks, unloaded, and stored. Bales left too long in the field can be damaged by rainfall and bales interfere with regrowth of the forage crop. If protected, hay retains most of its nutrients, but some losses in dry matter and nutrients occur. In a barn, hay continues to lose



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FIGURE 17-20
Hay is forage that is packaged and stored in the open air. Hay bales come in different sizes and shapes.

moisture to a moisture content of about 5 percent. Stored hay that is rewetted by rain or contact with the soil can mold, so inside storage is desirable. If hay is stored outside, it will have significant losses unless covered with plastic and placed on rock.

Silage

As a result of the significant field losses and challenges with achieving recommended moisture levels during haymaking, the ensiling process was developed. Silage is forage that is stored anaerobically (without air) at a moisture content above 60 percent in a specialized storage structure called a *silo*. The process of making silage is called **ensiling**. For silage, field losses are reduced compared to haymaking (Figure 17-21). Harvesting at a higher moisture content reduces field exposure to rain and leaf shattering. A storage structure or sealed package is needed to permanently exclude air and to prevent entrance of water from rain or snow. The high moisture content of silage is important for growth of beneficial bacteria and for compaction to exclude air.

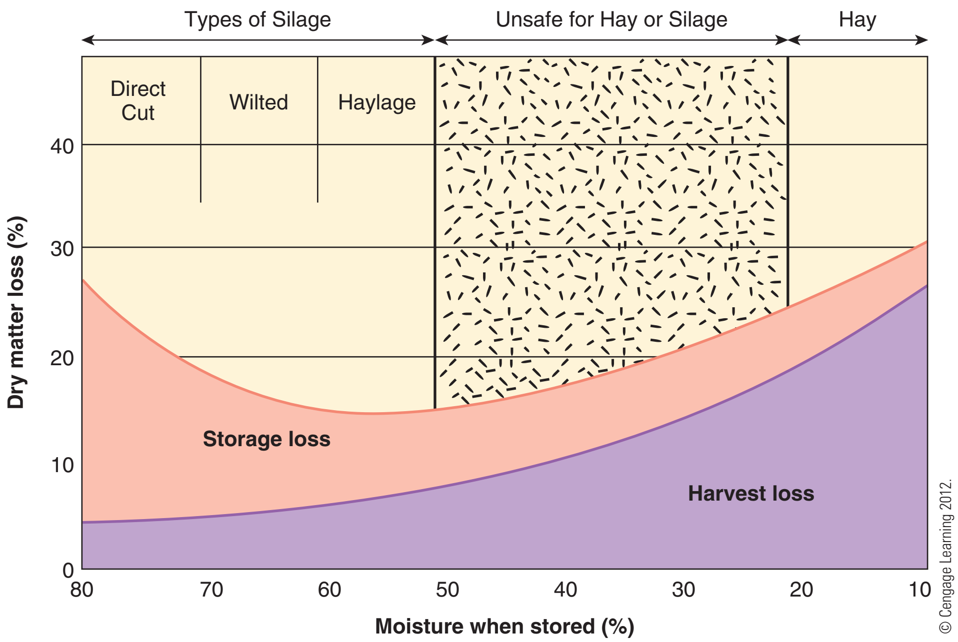


FIGURE 17-21
Generalized losses in dry matter associated with making hay and silage. Field losses are greater for haymaking because of leaf loss. Storage losses are greater than for silage making. In the unsafe range, forage is too wet for hay and too dry for silage.

Silage is preserved by a low pH caused by organic acids produced during biological fermentation. Organic acids such as lactic acid are produced by bacteria living on the forage.

Lactic acid reduces the pH to 4.5 or below, essentially "pickling" the forage. This low pH permanently preserves the forage and inhibits growth of fungi, bacteria, and yeasts. During the ensiling process, it is important that the forage material is compacted and that the air is excluded. Exposure to air during ensiling delays fermentation and can result in losses of energy and dry matter of the forage. Exposure of preserved silage to air can reverse the process and result in microbial growth.

Two Types of Silage

There are two main types of silage: corn silage and hay crop silage. **Corn silage** is made from finely chopped (1/2-inch or 1/3-centimeter in length) whole corn plants. The whole corn plant is immature relative to grain harvest and has a moisture content of 65 percent. Corn silage is a high-energy feed that is used in rations of livestock when high levels of gain or milk production are desirable.

Hay crop silage is made from legumes and grasses that can also be made into hay. These are lower in energy and higher in fiber and protein than corn silage. Small grains like wheat and barley can also be made into silage if harvested before mature. The three types of hay crop silage based on moisture content at ensiling are:

- **Direct cut silage** (75–85% moisture) is cut and chopped from the field, usually in the same day without significant drying. The high moisture content at harvest reduces field losses compared to harvesting at lower moisture levels, but the storage losses are greater because of incomplete fermentation.
- **Wilted silage** (60–75% moisture) is dried in the field until the target moisture is reached. It is then mechanically picked up and chopped. Field drying time can be from 4 to 8 hours.



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FIGURE 17-22
Tower silos used for aerobic storage of corn silage and hay crop silage. Within a tower silo, the pressure of the wet forage mass is important for excluding air from the silo.



Oregon State University, Forage Information System (2007).

FIGURE 17-23
Silage can be successfully made in disposable plastic containers. When high moisture bales are wrapped and made into silage, they are called *balage*. Silo bags are another approach to making silage. The key to successful silage making is to exclude moisture. These approaches are less costly than the large tower silos.

- **Haylage** (50–60% moisture) is the driest form of hay-crop silage. Haylage can be difficult to preserve and can spoil because it is difficult to pack and to exclude air from the chopped forage. It is often made in tower silos (Figure 17-22).

Advantages and Disadvantages of Silage

Preservation of high-moisture forage as silage has several advantages compared to hay. These include (1) less exposure to the weather during field drying, (2) more nutrients preserved due to reduced field loss, (3) more opportunity for mechanized handling and feeding and therefore fewer labor needs, and (4) potential for long-term preservation.

The primary limitation of ensiling relates to the cost of machinery and silos. However, lower cost approaches to ensiling have been developed that substitute labor for mechanical costs. These include:

- Balage—individual bags of baled silage wrapped in plastic (Figure 17-23)
- Silobags—large bags of silage
- Compacted piles and bunkers covered with plastic

How Farmers Determine the Moisture Content of Their Forage

We have discussed how important it is to know the moisture content of forage for effective preservation and storage as silage and hay. There are several approaches that are used to determine moisture concentration. The first is the hand (or grab) method that is a very subjective and likely the least accurate approach. It is used by experienced producers as a "ball park" indicator of moisture content. For this method, random handfuls of cut hay are obtained from the windrow and each handful is squeezed. Some general indicators are shown in Table 17-3.

The second approach involves the drying of several subsamples randomly collected from the windrow, using a microwave oven or a heating moisture tester. This method usually takes about 20 minutes and its accuracy is very much dependent on how representative the subsamples are. A scale is required to weigh the sample before and after drying. Moisture concentration is calculated using this equation:

$$\textit{Percent moisture (\%)} = \frac{\textit{(Initial weight} - \textit{Final weight)} \times 100}{\textit{Initial weight}}$$

The third approach is using an electronic moisture tester. These testers are based on the conductance of electricity through the forage. The more moisture in the forage, the greater will be the conductance. Electronic moisture testers need to be calibrated. Hand-held and equipment-mounted electronic moisture testers are available.

For more information on estimating forage moisture, see "Determining Forage Moisture Concentration" from Virginia State University at http://pubs.ext.vt.edu.

TABLE 17-3

Estimating forage moisture using the hand method. *Adapted from Gay et al. (2009).*

Condition of forage squeezed by hand	% moisture
Water is easily pressed out and forage retains shape	80 or above
Water can barely be pressed out and forage retains shape	75–80
Little to no water can be pressed out and forage retains shape	70–75
No water can be pressed out and forage falls apart slowly	60–70
No water can be pressed out and forage falls apart quickly	<60

Harvesting Other Crops

Crops that are not grains or forages have diverse harvesting methods. Cotton, tobacco, sugar beets, and potatoes are discussed in the following sections.

Cotton

Cotton is harvested primarily for the fibers that surround the cotton seeds, which are contained in bolls.

Maturity

Cotton is mature when the cotton bolls open to reveal the white fibers. Depending upon the method of harvest, harvest can begin with the first, sizeable opening of bolls or be delayed until the majority of bolls have opened. Although cotton is often an indeterminate plant, meaning it continues to flower and fruit over the course of the season, the majority of the harvest is derived from fruit set during the first four weeks of bloom.

Method of Harvest

Before harvest, cotton is usually defoliated. Plants are defoliated when bolls are 60–75 percent open by spraying chemicals. Low temperatures can also naturally cause the leaves to fall off. During the harvesting process, any remaining green leaves can stain the cotton fibers and decrease their marketability and quality. Cotton is harvested in two primary ways, using a picker or stripper (Figure 17-24). The cotton picker picks mature bolls as they are ready, so the process can be repeated multiple times as the bolls mature unevenly. Picker cotton varieties are often grown in areas with little risk of high winds during maturation and harvest of the cotton bolls. The other option for harvest is the cotton stripper, which removes all of the bolls, regardless of maturity, from the cotton plant at once. It also harvests any remaining plant matter, which must be removed before further processing.

Following the harvest, the cotton is packed and arranged into modules, a stack composed of 13–15 bales, which is compressed and tightly covered from the weather to ensure low moisture levels of the products. The modules are loaded onto trucks from the field to be transported to processing plants. Cotton modules are moved to processing plants where they are first ginned to remove seed and plant materials from the cotton fibers (Figure 17-25). The seeds are saved for cottonseed oil and cottonseed meal. The cleaned cotton fibers are compressed into 500-pound (230 kilogram) bales, which are then stored in climate-controlled warehouses.

Quality

Cotton quality is determined by the uniformity of the product coming into the mill and also the length, color, and softness of the cotton fibers. Longer cotton fibers are more desirable for spinning, as they can be twisted more to create higher quality fabrics and textiles. Cotton with less plant residue and staining, in addition to having low moisture content, has a higher postharvest quality.





FIGURE 17-24
Cotton harvesters. The above is a cotton picker and the below is a cotton stripper.



FIGURE 17-25
Cotton on the right has been ginned compared to the left which has not been ginned.

Tobacco

Tobacco is grown for its leaves for the production of cigars, cigarettes, snuff, and chew. Once leaves are harvested, several more steps are taken before going to market.

Maturity

Once flowers begin to develop, they must be removed, or topped, from the tobacco plant to allow the upper leaves to grow and thicken. Leaves begin maturing at the time of flowering and topping. Timing of topping is critical, as the quality of the leaves and overall yield can decrease if topping is delayed. Harvesting leaves too late can also lead to a decrease in quality.

Method of Harvest

Harvesting of tobacco can be done by picking only mature leaves (priming) as they develop or by cutting the entire plant. If the whole plant is harvested, only the leaves at adequate maturity are kept. Picking leaves as they mature can be accomplished by hand or mechanically. Cutting the whole plant can also be done by hand or machine.

Quality

The nicotine content of the tobacco leaves is the main factor in determining quality. The tobacco leaves from the tops of the plants are higher quality and are usually separated from the lower leaves. Tobacco is subject to many insects and diseases in the field, which can also affect quality.

Curing

After harvest, the leaves or stalks are tied up and hung for drying under controlled conditions, a process called *curing*. The curing process removes moisture and converts starches to sugars in the leaves, which enhances flavor development. There are four main methods for curing tobacco: with forced air (air-curing), with smoke (fire-curing), with heat (flue-curing), and by the sun (sun-curing). The type of curing process depends upon the tobacco variety and the end-use product. After curing, the tobacco is stored in well-ventilated bales until it is needed to make tobacco products.

Sugar Beets

In the production and harvest of sugar beets, emphasis is placed on yield of sugar per acre. Sugar beets are treated as an annual crop with roots harvested in the fall of the year. Harvesting of sugar beets involves removal of green leaves and lifting the root from the soil with a minimum of damage.

Maturity

In the fall of the growing season, sugar beets are at an appropriate developmental stage for harvest. Sugar content of the sugar beets is the most important factor in payment to farmers, rather than the weight of the beets, so harvest maturity must optimize sugar concentration in the roots. In regions where the ground freezes, sugar beets must be harvested before the soil freezes over, regardless of developmental stage.

Harvest

Harvest of sugar beets begins with topping the plants during late fall of the growing season. A mechanical defoliator removes the foliage (topping) and cuts a thin section of the crown from the top of the beet. The crown often is contaminated with a small amount of soil that is difficult to remove by washing. Next, the roots are harvested using a harvester or digger to remove the roots from the field with a minimum of soil. The subsequent harvesting step must occur within 24 hours of topping, or the roots will begin to use up stored sugar reserves to start regrowth of the foliage. The beets are stored to maintain as much sucrose as possible, which means keeping them alive by reducing root respiration and preventing freezing and thawing cycles. The beets are deposited into trucks and taken to processing facilities where they are stored in piles until they can be utilized in the factory.

Storage

Because of the size of the harvest, sugar beets are often stored up to 6 months until processing. The optimum temperature to minimize respiration and loss of sugars is about 32°F (0°C). Outside storage areas often have forced-air aeration systems to keep the beets at a uniform temperature and moisture. Some facilities utilize climate-controlled, indoor storage.

Quality

The quality of sugar beets is determined by the concentration of sucrose within the roots, which generally ranges from 15–20 percent by dry mass. If beets are not topped properly, or are exposed to freezing and thawing temperature cycles, sugar content can decrease and other carbohydrates can build up in the tissue, lowering the quality of the harvest.

Potatoes

Like the sugar beet, the harvestable portion of the potato crop, the tuber, is underground and specialty equipment is required for harvest.

Maturity

It takes roughly 100–120 days for potato tubers to reach physiological maturity. However, because potatoes are edible at any stage of their development, the end use may determine when potatoes will be harvested. For example, smaller, early or new potatoes are dug long before the maturity stage of baking or chipping potatoes. Potatoes for baking or chipping are analyzed for maturity in the field by chemically monitoring the sugar content of the tubers. Immature tubers have a higher sugar content than mature tubers. A high sugar content can lead to discoloration during processing for chips or fries.

Harvest

Once potatoes have reached desired size, harvest starts after the potato vines have been chemically desiccated or mechanically destroyed. Once the vines are killed, the tubers are allowed to mature for several weeks before harvest. During harvest,

potatoes are dug and loaded into trucks. The machinery also shakes soil from the potatoes to reduce transportation and processing costs. Throughout harvest, tuber bruising or skinning, which can occur from the harvest machinery, must be minimized. Bruised tubers can negatively impact the storage capacity of potatoes and provide an entry point for fungal and bacterial disease. Following harvest, the potatoes are washed, graded, and packed for sale and transport.

Quality

For chipping and processing, quality is determined by factors that include skin thickness, potato shape, starch content, flavor, texture, color, and density. Quality can be impacted in the field by soil moisture, temperature, frost, insects, and disease pressure. Quality can also be negatively impacted through improper storage temperatures and postharvest disease and decay.

Storage

The conditions for potato storage depend upon the variety of potato and the end use. Ideally potatoes should be stored at 40 to 42°F (4 to 6°C) to keep the tubers alive, maintain starch content, and prevent excess respiration. Potatoes stored at improper temperatures will convert starches to sugars to initiate sprouting and regrowth that reduces the product quality (Figure 17-26).



Peggy Greb, USDA-ARS.

FIGURE 17-26
Sprouting of potatoes during storage reduces quality.

Review Questions

1. What is the main goal of harvest and storage systems?
2. Why is it important to determine when physiological maturity has been reached?
3. Why is additional dry down of grain often required before storage?
4. What can happen to grains if they are stored at greater than recommended moisture levels?
5. Describe the different ways in which forages are harvested.
6. Distinguish between continuous and rotational grazing.
7. What are the main differences between hay and silage?
8. Identify crops that are made into hay and silage.
9. What happens to hay if it is stored at a moisture content that is higher than 20 percent?
10. How is silage stored?
11. How is the maturity of cotton determined?
12. Name four methods for curing tobacco.
13. Potatoes and sugar beets are grown for their underground tubers or roots. How does the harvesting process for these two crops compare?

Critical Thinking

1. In your state, what are the important crops that are harvested and when are they harvested?
2. Do you think that animals need to be pastured, or should they be confined and fed hay or silage?
3. Many inventors have made significant advances in agricultural machinery. These include Cyrus McCormick, Obed Hussey, John Deere, James Oliver, and Eli Whitney. For two of these inventors, identify their invention(s) that advanced agriculture. In addition, indicate the time in which they lived, where they lived, and where their inventions were used.

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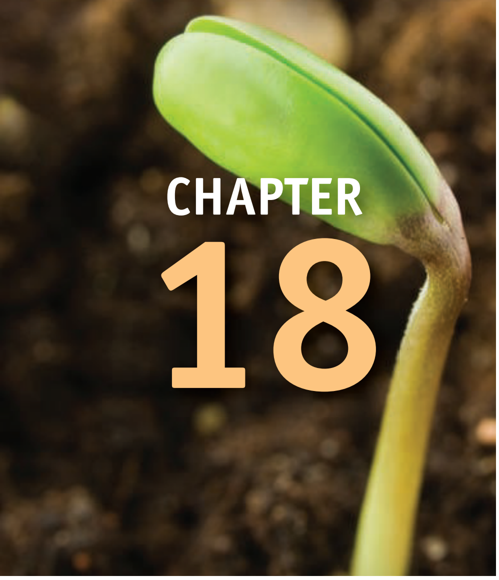
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CHAPTER 18



Organic Agriculture





Key Concepts

- Organic production is a system that is managed in accordance with the Organic Food Production Act of 1990.
- Organic agriculture promotes and enhances biodiversity, biological cycles, and environmental stewardship.
- Organic farmers are inspected by independent certifying agencies and must follow specific crop and livestock production guidelines.
- Organic regulations do not allow application of synthetic fertilizers, pesticides, or use of genetically engineered products.
- Total organic acreage comprises less than 1 percent of the total cropland.
- Weed control and fertilization are two of the largest challenges facing organic crop producers.

Key Terms

broadcast cultivation
conventional agriculture
cultivating tillage
cultural weed control
flame weeding
interrow cultivation
mechanical weed control
National Organic Program (NOP)
nitrogen credit
organic agriculture
organic certification
organic system plan (OSP)
primary tillage
secondary tillage

Introduction

Organic agriculture is a food production system that is an alternative to conventional agriculture. **Conventional agriculture** uses industrialized, modern methods such as synthetically produced chemicals and transgenic crops as described in many chapters of this book. In contrast to conventionally produced food, organic food is produced, processed, and handled under national standards established by the National Organic Standards Board. The organic industry is "consumer driven" and is related to consumer demand for products that are considered healthy and pesticide free. An organic logo provides consumers with verification that the food they purchase has been produced and processed using acceptable organic practices (Figure 18-1). Today, food that is produced using organic standards is "certified organic." Organic crop and livestock production are small but growing parts of agriculture.

Both conventional and organic agriculture depend on the soil as the medium for growth, but production practices differ. Organic crop production is regulated and inspected by an independent certifying agency. Growers must develop and adhere to an "organic systems plan"; manage their soil resource responsibly; follow rules that include no synthetic fertilizers or pesticides, antibiotic inputs, or genetically engineered seeds or plants; and use a diverse crop rotation. Organic crop producers perform more labor and rely on cultural practices, mechanical weed control, and green manures for crop production.

Consumer-Driven Food Production

Organic food sales have increased nearly 500 percent since 2000 and are now worth nearly $25 billion (Figure 18-2). Although organic sales are still less than 5 percent of the total U.S. food sales, this trend is expected to continue increasing despite the fact that organic food products are generally more expensive than conventionally produced food products. The organic market is "consumer driven" and consumer choices influence the types of foods grown and marketed. Vegetables and fruits account for about 40 percent of the market sales, while dairy products, primarily milk, account for nearly 12 percent of the sales. There is also a

FIGURE 18-1
The USDA Organic Seal. This logo can only be used for products that are composed of at least 95 percent certified organic ingredients.

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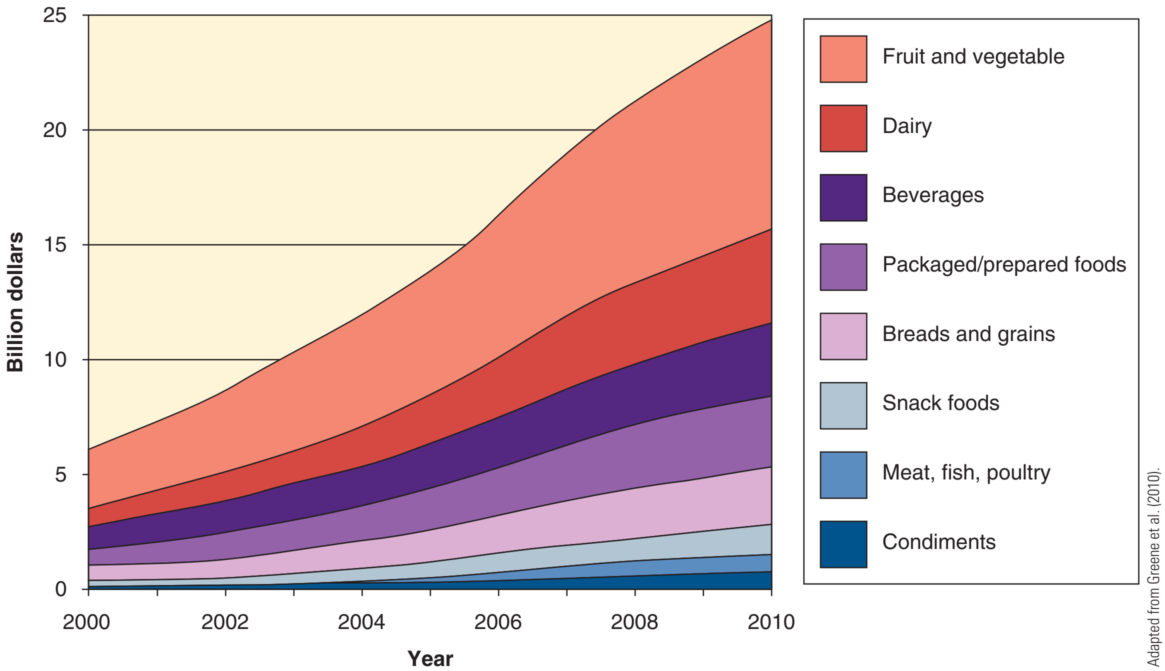


FIGURE 18-2 U.S. organic food sales by food type. Total sales reached almost $25 billion in 2010.

great increase in processed products that use organic ingredients. Crops are used as ingredients in prepared foods such as pizza and frozen entrees, breads, and even snack foods like corn chips.

The organic foods industry originated with local production and marketing, and there was often a personal relationship between the grower and consumer. Now many organic foods are transported great distances. Organic foods continue to be sold in most health food and nutritional stores and now are featured in organic food aisles of supermarkets and other national food retailers. The rise in organic sales has been influenced in part by the development of an **organic certification** program.

U.S. Government Certification

A legal definition of organic production as well as regulations were established to protect consumers by ensuring that certain standards are met during production, handling, and processing of crops and foods. Organic production is a system that is managed in accordance with the Organic Food Production Act of 1990. (See http://www.ams.usda.gov for more information.) The USDA's **National Organic Program (NOP)** is the federal program that regulates organic agriculture in the United States. The NOP defines organic agriculture as "an ecological production management system that promotes and enhances biodiversity, biological cycles, and soil biological activity. It is based on minimal use

of off-farm inputs and on management practices that restore, maintain, or enhance ecological harmony."

Organically certified products should not be confused with those that are called *natural* or *local*, as these are produced without any standards. Therefore, while consumers can assume that foods bought at a "local" farmers' market are produced nearby and that "natural" food is produced with minimal inputs, "natural" and "local" are not legally defined, so there are no guarantees regarding how or where the food is produced.

The National Organic Program develops, implements, and administers national production, handling, and labeling standards. Certification is a key aspect of the NOP quality-control program. Farmers who sell over $5000 of agricultural products to be sold as "100 percent organic" need to be certified. Likewise, processers or marketers of products labeled as "organic," or "made with organic ingredients" need to be certified. An independent "certifying agency" accredited by the USDA is responsible for certification. The USDA maintains a listing of certifying agencies within each state of the United States and internationally.

To become certified, farmers must apply to an approved certifying agency providing information such as the type of crop or livestock to be grown, the 3-year history of fertilizer and pesticide inputs to the land, and a plan that specifies how their farm will be managed to comply with organic goals. The farm and farmer are then inspected by the certifying agency. Inspectors review the records maintained by the farmer and view farming practices. If the farmer meets all the criteria, the farm operation will be "certified organic"; however, the farm is reinspected annually to renew certification. Farms can be "decertified" if they fail to meet all the standards. Details of standards are provided at the USDA's NOP website. Some of the basic requirements for organic certification are:

- Three years with no application of prohibited materials (synthetic fertilizers, pesticides, or genetically modified organisms [GMOs]) prior to harvest of the first certified organic crop
- Implementation of an organic system plan, with: proactive fertility systems; conservation measures; environmentally sound manure-, weed-, disease-, and pest-management practices; and soil-building crop rotations
- Use of only natural inputs and approved synthetic substances on the National Organic Program list (Table 18-1)
- No use of genetically engineered organisms defined in the rule as "excluded methods" that have unknown risks
- No sewage sludge
- Use of organically produced seeds, when they are commercially available
- Use of organic seedlings for annual crops
- Following regulations on use of raw manure and compost
- Maintenance of buffer zones, depending on risk of contamination

Record Keeping

Sound planning and record keeping are important for both conventional and organic farmers, but development of a cropping plan and record keeping are required for organic certification. First, producers are required to have an **organic system**

TABLE 18-1

Examples of allowed inputs for organic production. *Adapted from the USDA's National Organic Program (2010).*

Amendment
Manure
Compost
Kelp meal and other aquatic plant extracts
Elemental sulfur
Humic acids (naturally occurring)
Magnesium sulfate
Soluble boron
Liquid fish products
Lime (naturally occurring)
Rock phosphates
Blood meal
Soybean meal
Bone meal
Alfalfa hay meal
Corn gluten

plan (OSP) that describes the practices conducted in their operation to produce organic products. The OSP is completed at the start of the certification process and is updated annually. Producers must keep records on the production, harvest, and handling of crops and livestock management that demonstrate adherence to NOP rules. Records must be accessible and easy for inspectors and certifying agencies to comprehend.

Organic Agriculture Is Growing

Organic agriculture has been the fastest growing component of crop and livestock production in the United States. Organic acreage has increased nearly 400 percent since the first estimate in 1992, but total organic acreage represents less than 1 percent of the total U.S. cropland acreage. There are about 4.8 million acres of certified organic farmland in the United States. This comprises 2.7 million acres of cropland and 2.1 million acres of rangeland and pasture (Tables 18-2 and 18-3).

All states had some organic acreage in 2008, with the leading states being California, North Dakota, Montana, Minnesota, and Wisconsin. For most states except California, organic acreage is devoted to field crops or pasture; California is unique in that over half the acreage is used for production of fruit, vegetable, and other crops such as cotton, peanut, and potato (Figure 18-3).

In 2007, there were about 20,000 certified organic farms in the United States with about 70 percent of those less than 50 acres in size (Figure 18-4). The average organic farm was 126 acres, compared with 444 for conventional farms. Larger acreage farmers with $50,000 or more of sales make up only about 23 percent of the total farms but produce about 93 percent of the total sales (Figure 18-5). Small organic farms often specialize in vegetable and poultry production. The reduced farm size for organic compared to conventional farms (average size 444 acres) is likely due to the requirements for mechanical weed control or manual labor that limit the land area that can be managed.

A diversity of agronomic crops is grown in organic systems because of the requirements for long-term rotations, generally with a minimum of three crops. Because of the large, organic human food and livestock feed markets, corn, wheat, and soybean are commonly grown, but they still each represent less than 1 percent of the total U.S. farm acres. In some regions with favorable climates and where local markets exist, dry peas, dried beans, lentils, and flax are grown. Forage crops are essential ingredients in diets for organically produced ruminant animals. Alfalfa and red clover are grown to provide feed for the beef and dairy industries,

TABLE 18-2

U.S.-certified organic farmland acreage and livestock number, 1992, 2000, and 2008. 1 acre = 0.4 hectare. *Adapted from the USDA-ERS (2010).*

	Acres		
Land	**1992**	**2000**	**2008**
Pasture/rangeland	532,050	557,167	2,160,577
Cropland	403,400	1,218,905	2,655,382
	Number		
Animals	**1992**	**2000**	**2008**
Total livestock	11,647	56,028	475,829
Beef cows	6796	13,829	63,680
Milk cows	2265	38,196	249,766
Hogs and pigs	1365	1724	10,111
Sheep and lambs	1221	2279	7455
Total poultry	61,363	3,159,050	15,518,075
Layer hens	43,981	1,113,746	5,538,011
Broilers	17,382	1,924,807	9,015,984
Turkeys	—	9138	398,531

TABLE 18-3

U.S.-certified organic acreage of different crops in 1995, 2000, 2005, and 2008. 1 acre = 0.4 hectare. *Adapted from the USDA-ERS (2010).*

	Certified organic acreage			
Crop	**1995**	**2000**	**2005**	**2008**
Grains				
Corn	32,650	77,912	130,672	194,637
Wheat (plus spelt)	120,800	206,474	293,824	415,902
Oats	13,250	29,771	46,465	57,374
Barley	17,150	41,904	39,271	46,954
Beans				
Soybeans	47,200	136,071	122,217	125,621
Dry beans	—	14,010	10,561	16,465
Oilseeds				
Flax	5850	25,076	30,843	21,554
Sunflowers	14,200	19,342	6087	18,777
Hay and silage	**84,100**	**231,207**	**411,342**	**793,442**
Vegetables				
Tomatoes	—	3063	6655	9237
Lettuce	—	11,410	11,986	27,796
Carrots	—	5665	5737	24,576
Fruits				
Citrus	—	6509	10,152	14,065
Apples	—	9270	12,772	17,626
Grapes	—	12,575	22,800	28,289
Other cropland				
Cotton	32,850	15,027	9537	15,377
Peanuts	—	2085	11,940	16,776
Potatoes	—	5433	6581	8273

while perennial grasses and legumes are used in pastures that are required for organic livestock production. In addition, alfalfa and red clover are often grown as green manure crops to supply N to corn, sorghum, or small grains in rotation.

Organic livestock production has also increased significantly. The predominant large-animal breed is dairy cattle for milk production; layer and broiler chickens are predominant among poultry. In local markets, organic growers produce seasonal specialty poultry like heirloom turkeys for Thanksgiving.

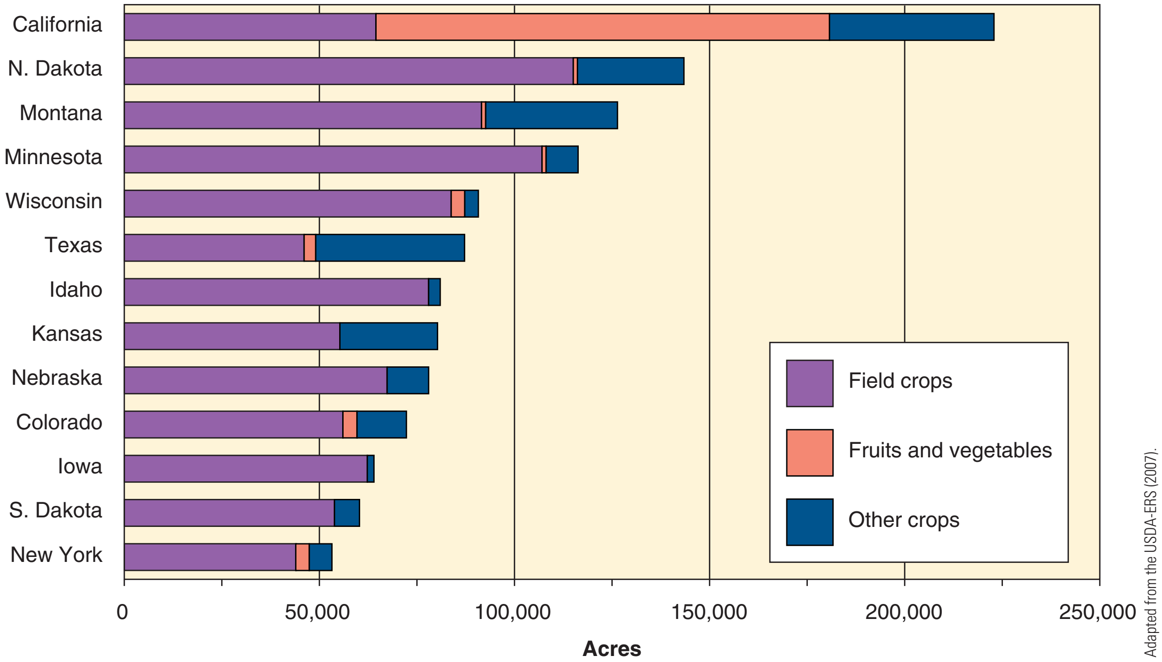


FIGURE 18-3 Organic cropland by type—field crops, fruit and vegetable crops, and other crops.

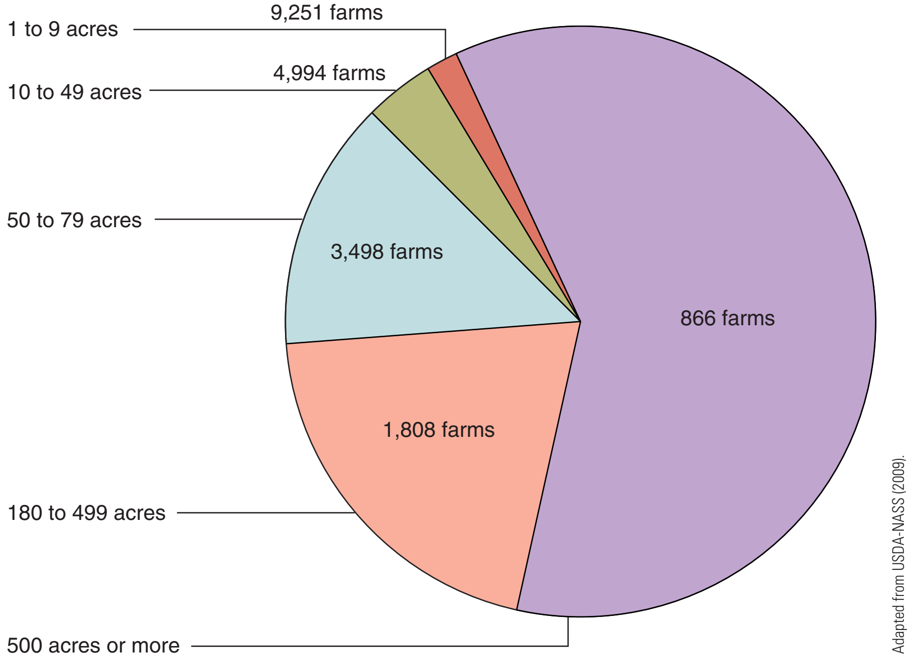


FIGURE 18-4 Size of organic farms and percentage of total production in 2007.

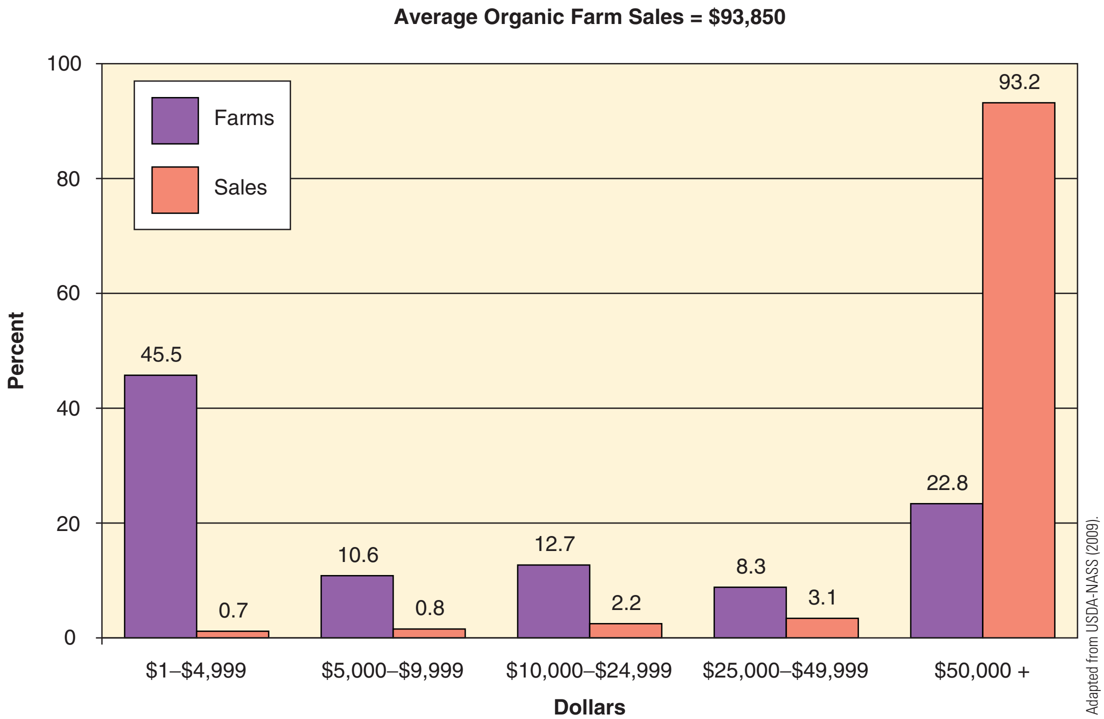


FIGURE 18-5 Distribution of organic farms and sales by sales class in 2007.

Why Farm Organically?

Many of the ongoing organic production practices are not new and are similar to those used by farmers before the industrialization of agriculture. On farms prior to World War II, it was commonplace to have rotations of diverse crops including forages used to feed livestock and to supply nitrogen to subsequent corn crops. These crop rotations reduced economic risk and weed problems on the farm. Many farms had poultry, swine, and cattle for family consumption and local marketing. Livestock generated manure for crop fertilization. Today's organic farmers also value diverse crop rotations and livestock manures, but utilize modern machinery and improved crop varieties.

Organic producers have several reasons for farming organically. They are concerned about the impact of synthetic pesticides and fertilizers on human, livestock, and environmental health, about GMO crops, and about the effect antibiotic applications to animals can have on human and animal health and environmental quality. They want to reduce off-farm purchase of inputs, are committed to stewardship of the land, and are concerned about the effect of simplified, annual crop rotations on long-term soil health and productivity. Price premiums paid for organic crops may influence some to farm organically (Table 18-4); however, these are necessary to make up for the greater labor cost and sometimes lower yields. Surveys show that about half of the certified organic producers transition from conventional farming, while half had already used organic production practices before certification.



Local Foods

Local food systems have grown in popularity in recent years owing to increased consumer demand. Local foods are considered to be those that are produced, processed, transported, and sold within a certain vicinity. Types of local food systems can include:

- Community-supported agriculture (CSAs)
- Direct-to-consumer farm marketing
- Farmers' markets
- Farm-to-school or farm-to-institution marketing
- Other wholesale or retail (co-ops, grocery stores, farm stands, etc.)

While the term "local" has numerous implications, there is currently no consensus about what geographical distance between production and consumption of food products constitutes "local." Definitions vary by state, region, markets, retail outlet, and consumer. In 2008, the U.S. Congress stated in the Food, Conservation and Energy Act that food products that travel less than 400 miles to their destination can be considered "local." However, this definition has not been universally accepted and debate continues about the geographical range of a local agricultural product. Some consumers consider a 40-mile radius to be locally produced, while other consumers feel that any product produced in their home state is local. Currently, small farms, with less than $50,000 in total sales, provide the majority of local food.

Local foods and the systems that support them have been increasing. In 2010, the USDA Economic Research Service reported that farm-to-consumer food sales rose from $551 million in 1997 to $1.2 billion a decade later, constituting 0.8 percent of total agricultural sales. Farmers' markets, CSAs, and farm-to-school programs have also increased significantly in the past decade.

Concerns about the ecological and energy costs of long-distance food transportation, corporate food systems, and increasing numbers of food-safety problems are factors promoting consumer-driven local food systems. In addition, there is increasing preference for supporting local farmers and businesses, and choosing food products that are high-quality and at the peak of freshness and taste. Consumers are often willing to pay more for locally produced products for many of the same ideological reasons.

TABLE 18-4

Examples of wholesale price differences for organic versus conventional crops for August, 2010. Organic farmers can get even higher prices for food-grade crops. *Adapted from the USDA–Agricultural Marketing Service (2010).*

Crop	Organic	Conventional
Corn, feed	4.75	3.89
Soybean, feed	15.50	10.39
Wheat (SRW)	4.91	4.16
Oats, feed	3.50	2.72
Corn, food grade	6.92	—
Soybeans, food grade	20.16	—

Organic Production Practices

Organic agriculture is an ecologically based management system. Some of the major differences between organic agriculture and conventional agriculture are listed in Table 18-5.

In addition to the factors mentioned in Table 18-5, organic production can place greater demands on the producers' management skills and time compared to conventional production, which attempts to replace human inputs with technology inputs. This is especially the case with the use of herbicides for weed control. Many herbicides used for weed control require a single application, whereas for organic weed control, multiple cultivations and more time are usually required (Table 18-6). The demands on time for organic producers will be magnified as farm size increases, which in part explains why organic farms on average are smaller than conventional farms.

Organic Yields and Profit

A common perception is that organic agriculture is less productive than conventional agriculture. Results of research on the relative yield of organic and conventional crop production are inconsistent. Generally, for forages like alfalfa and many small grains, the yields of organic and conventional will be similar, while relative yields of row crops like corn or soybean will vary depending on management and environment (Tables 18-7 and 18-8). With adequate weed control and fertility, the yields of conventional and organic crops should be comparable.

TABLE 18-5

Side-by-side comparison of organic and conventional agriculture.

	Organic agriculture	Conventional agriculture
Fertility	Nonsynthetic amendments like manure, compost, and green manures; legumes in rotation	Primarily synthetic fertilizers
Weed control	Multiple strategies including: diverse rotations, mechanical weed control, cultural weed control	Primarily synthetic herbicides, herbicide-resistant transgenic crops
Insect control	Diverse rotations, some nonsynthetic insecticides	Primarily synthetic insecticides, insect-resistant transgenic crops
Crops	Nongenetically modified only	Either transgenic or traditionally bred
Rotations	Diverse rotation with three or more crops	Often includes just corn and soybean; continuous cropping of corn is possible
Profits	Can be comparable to conventional	Can be comparable to organic
Inputs	Fewer inputs	Greater inputs
Labor	Depending on crop, more time may be spent in the field	Depending on crop, less time may be spent
Yields	Corn and soybean yields have potential to be lower, but small grains and forages can have similar yields	Can be higher yielding, especially corn and soybean

TABLE 18-6

Hours spent per acre for organic and conventional corn and soybean production in Minnesota and Iowa. *Adapted from the Minnesota Department of Agriculture (2008) and Delate et al. (2006).*

		Organic		Conventional	
Crop	Location	Hours/acre	Hours/hectare	Hours/acre	Hours/hectare
Corn	Minnesota	2.8	1.1	2.6	1.1
Corn	Iowa	2.2	0.9	1.2	0.5
Soybean	Minnesota	3.3	1.3	1.9	0.8
Soybean	Iowa	3.6	1.5	1.1	0.4

Although yield of crops may sometimes be lower and labor inputs higher, organic crop production can be profitable (Table 18-9). This occurs because purchased costs are lower and because there is a premium paid for organic crops. The premium occurs because there is a high demand and inadequate production.

TABLE 18-7

Summary of experiments that compare yields of organic and conventional crops. Shown are the ranges of organic yields as a percentage of conventional yields. *Adapted from Posner et al. (2008).*

Crop	% of conventional yield (ranges)
Corn	72 to 114
Soybean	64 to 111
Small grains	90 to 100
Forages	96 to 100

TABLE 18-8

Yields of organic and conventional crops at Lamberton, MN 1993–1999. The rotation was for 4 years (corn-soybean-oat/alfalfa-alfalfa). *Adapted from Porter et al. (2004).*

Crop	Conventional		Organic	
Corn	137 bu/ac	8599 kg/ha	129 bu/ac	8097 kg/ha
Soybean	43 bu/ac	2892 kg/ha	34 bu/ac	2287 kg/ha
Oat	52 bu/ac	1865 kg/ha	52 bu/ac	1865 kg/ha
Alfalfa	5 ton/ac	11 tonnes/ha	5 ton/ac	11 tonnes/ha

TABLE 18-9

Net returns of conventional and organic crops with and without organic premium at Lamberton, MN 1993–1999. The rotation was corn-soybean-oat/alfalfa-alfalfa. Even without premiums, organic net returns can be similar to conventional. *Adapted from Mahoney et al. (2003).*

System	Net return per acre
Conventional	$172
Organic, no premium	$175
Organic, with premium	$270

Weed Control in Organic Agriculture

Weed control has been identified by organic producers as one of the biggest challenges in crop production. Weeds are controlled by several approaches including the use of weed-free seed and hay, cultural weed control strategies, and mechanical tillage.

Cultural Weed Control

Cultural weed control uses methods to modify the cropping system or a specific crop's production to reduce weeds. These methods include rotation, cover crops or mulches, and delayed planting.

Rotation

Diversified crop rotations are effective against weeds. Varying crops by different planting dates (e.g., wheat is planted several weeks before soybean) or growing a perennial crop along with row crops can prevent weeds from adapting to the planting regimen. The crops included within a rotation are important. Competitive perennial crops such as alfalfa, or cover crops like winter rye, can help prevent weed infestations. Following are two rotations that differ in number of crops:

- A 5-year rotation of corn-soybean-small grain/alfalfa-alfalfa-alfalfa is particularly effective against weeds. With alfalfa, the soil will have year-round coverage for 3 years. Oat, wheat, or barley could be used as the small grain crop. Including alfalfa that is cut and harvested during the growing season eliminates many annual and perennial weeds that are prevalent in corn and soybean. Likewise, cultivating corn and soybean can reduce perennial weeds that invade alfalfa.
- Corn-soybean-small grain/red clover. This rotation is common for producers who do not have livestock. The red clover can be clipped in the fall and then terminated in the spring before corn planting. This weed control is less effective than for the rotation with the multiple years of alfalfa.

Smother and Cover Crops

A smother crop is a vigorously growing crop that growers use to suppress weeds. Generally, a smother crop is not harvested, but instead plowed down. Two examples of summer smother crops used in the Upper Midwest are buckwheat and Sudan grass (or sorghum–sudan grass). These crops are planted using a grain drill in spring after the danger of frost is past. They have good seedling vigor and form a dense stand that shades many weeds.

Winter rye is a winter cover crop that is planted in the fall after harvest of corn, small grain, or soybean and can be used as a smother crop. Its fall and spring growth can physically suppress weeds by competing for light and water, and its herbage contains allelochemicals that can interfere with weed growth (Table 18-10). Spring growth can be tilled under or used as a surface mulch.

TABLE 18-10

Cover crops with allelopathic effects on different weeds. *Adapted from various sources.*

Cover crop	Weeds inhibited
Brassicas	Pigweeds
	Shepards purse
	Green foxtail
	Kochia
	Hairy nightshade
	Barnyard grass
Winter rye	Wild oat
	Dandelion
	Crabgrass
	Barnyard grass
	Common ragweed
	Common lambsquarters
	Pigweed
	Purslane
Hairy vetch	Common chickweed
	Redroot pigweed
	Wild carrot
	Knotweed
	Common lambsquarters
	Nightshades

Other cover/mulch crops that can suppress weeds include hairy vetch, forage radish, and oilseed radish. Hairy vetch is typically planted in late summer to early fall and, in addition to providing winter cover, it contributes nitrogen through the process of biological dinitrogen fixation. Forage radish and oilseed radish do not conduct nitrogen fixation but can scavange soil nitrogen and, because of their large tap roots, can act as "biodrills" in loosening compacted soil.

Delayed Planting

Many research results show that delayed spring planting beyond dates recommended by agronomists (see Chapter 14) can have a negative effect on crop yield. However, for many organic farmers, delayed planting can be the correct choice in highly weed-infested fields. Delaying planting allows for more mechanical weed control operations to be performed prior to crop planting with the prospect of a



Diversity in Organic Rotations

Organic farmers often have more diverse rotations than conventional farmers. An organic farmer in Minnesota may grow barley, oats, wheat, flax, field peas, red clover, and alfalfa, in addition to corn or soybean, while a conventional farmer may grow only corn and soybean. Some organic farmers use corn minimally in their rotations due to its high nutrient and moisture needs. An example of a longer rotation would be corn-soybean-small grain/alfalfa-alfalfa-alfalfa-alfalfa. Flax and field peas can be used in the place of the small grain. Success is due in part to the ability to be flexible in rotation. Markets and time constraints for planting must be considered before deciding how much of each crop to plant.

reduced weed population growing with the crop. Delayed planting is particularly advantageous for warm-season crops like corn and soybean (Figure 18-6). Cool-season crops like small grains or field pea that are planted early in the spring are not likely to benefit from delayed planting. Organic farmers in the Upper Midwest balance the potential yield gains from improved weed control against potential yield losses from delayed planting by planting corn around May 15 and planting soybean between June 1 and June 15.

Mechanical Weed Control

Most organic producers use **mechanical weed control** in addition to cultural methods. Effective mechanical weed control can best be achieved using a diversity of equipment that provides options to eliminate weeds at different stages of crop growth. Lack of favorable weather or soil conditions in which to perform a mechanical weed control operation in a timely manner is one of the biggest reasons for weed control failure and, as a consequence, reduced crop yields. Some of the broad categories of mechanical weed control are primary tillage, secondary tillage, cultivating tillage, and flame weeding.

Primary and Secondary Tillage

Primary and secondary tillage are used for seedbed preparation and residue incorporation, but they can also greatly affect weed populations. **Primary tillage** is performed with moldboard, chisel, and disk plows (see Chapter 14). Primary tillage can bury some weed seeds so they cannot germinate, but it can also bring other seeds to the surface, allowing them greater opportunity for germination. Primary tillage can kill annual weeds that have germinated and suppress some perennial weeds (Table 18-11), but it can also spread vegetative propagules of quack grass and Canada thistle. The type of tillage equipment

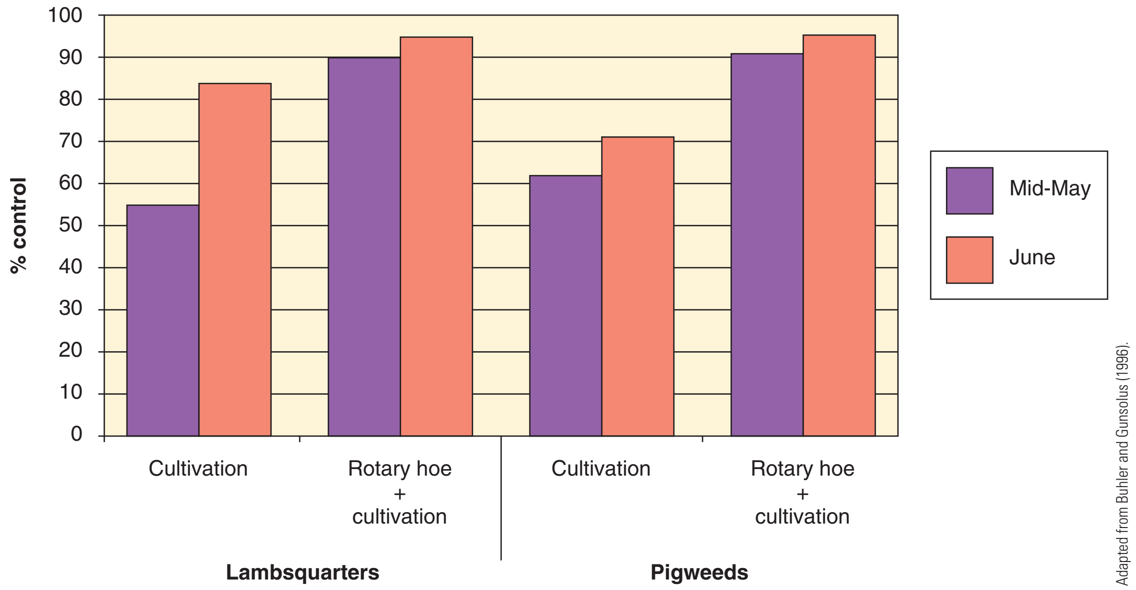


FIGURE 18-6 Delayed soybean planting effects on control of lambquarters and pigweeds in Rosemount, MN, 1989–1991. Soybeans were cultivated or rotary hoed and cultivated.

TABLE 18-11

Primary tillage equipment effectiveness in managing different perennial weeds. Primary tillage is more effective if it is done before active growth or flowering because it reduces weeds' energy reserves. *Adapted from Liebman et al. (2001).*

Weed species	Growth habit	Moldboard plow	Chisel plow
Canada thistle	deep rhizomes	Fair	Poor
Common milkweed	deep rhizomes	Fair	Poor
Common plantain	fibrous root	Good	Fair
Curly dock	taproot	Good	Fair
Field bindweed	deep rhizomes	Fair	Poor
Field sowthistle	shallow creeping roots	Fair	Poor
Nutsedge	bulb	Fair	Poor
Quack grass	shallow rhizomes	Fair	Poor

used can affect weed control. Moldboard plowing generally buries weed seed deeper than chisel plowing.

Secondary tillage further breaks up the soil to destroy weeds and prepare the seedbed. Field cultivators and harrows are used for secondary tillage. The timing of seedbed preparation affects how many weeds are destroyed. For example, in the

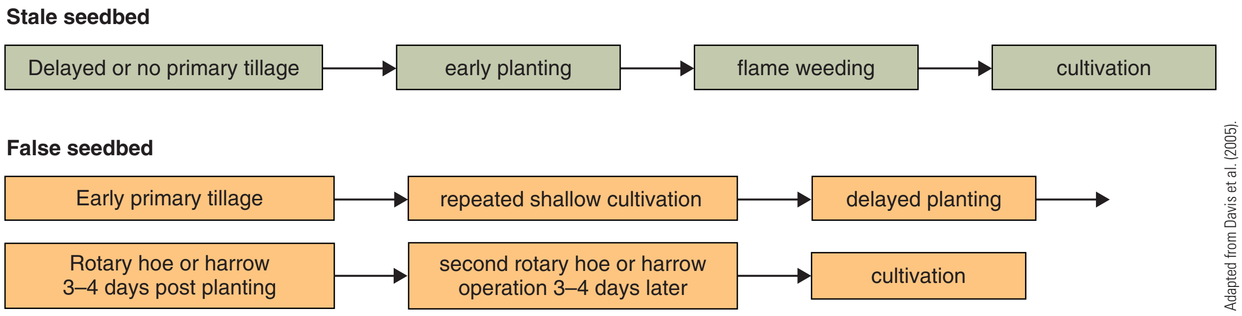


FIGURE 18-7 Diagram of stale and false seedbed techniques in organic systems. In the Upper Midwest, false seedbed is more commonly used.

Midwest, weeds that emerge early like common lambsquarters can be controlled by seedbed preparation, while later emerging weeds like pigweeds may have to be controlled at a later date with cultivation. Secondary tillage weed-control techniques include stale and false seedbeds (Figure 18-7). Often, secondary tillage is used repeatedly to enhance weed germination to deplete the weed seed bank. The weeds germinate in a flush that can be controlled with further, shallow secondary tillage without consequence, because the crop has not been planted.

Cultivating Tillage

Cultivating tillage is performed after the crop is planted. Cultivation kills weeds by burying them, breaking them apart, or drying them out. In addition to controlling weeds, cultivation can break up soil crusting, which can increase crop emergence, water infiltration, mineralization of nutrients, and soil aeration. A short window of time usually exists for timely use of cultivation. Weeds that emerge before or with the crop are the most critical to eliminate. Weeds that emerge after crop emergence will have less negative impact on yield. The types of cultivation are broadcast cultivation (blind or full-field cultivation without regard for crop rows) and interrow cultivation (between crop rows).

Broadcast cultivation can be performed before or after the crop emerges (see next section). Preemergence cultivation is done with chain harrows, flex-tine harrows, spring-tooth harrows, spike-tooth harrows, and rotary hoes and affects the top 0.5–1.5 inches (1 to 4 centimeters) of the soil depending on the equipment (Figure 18-8). These tools are most effective under hot and dry conditions so the weeds near the surface will dry out. Preemergence cultivation is done 3 to 5 days after the crop has been planted. Broadcast or blind cultivation can be performed with harrows and rotary hoes after the crop has emerged. However, this type of cultivation has the greatest risk for crop damage, and crop planting rates may need to be increased to compensate for this field operation.

Interrow cultivation controls weeds that grow between the rows, and therefore is used only in row crops like corn, soybean, or field beans. Row crop cultivation is secondary to the weed control operations that were performed earlier, because the earlier emerging weeds are more critical to control due to their greater potential to reduce crop yield. Interrow cultivation is done 3 to 5 weeks post plant-



FIGURE 18-8
Flex-tine weeder. The tines pull up the small weeds, but not the deeper-rooted crop in the soil.

ing. Tools used for interrow cultivation include cultivators, discs, rotary cultivators, rolling cultivators, basket weeders, and rolling harrows.

Interrow cultivation is low risk to the crop compared to postemergence broadcast operations. Because cultivation is performed between the rows, the crop should not be directly affected by the machinery. Cultivation is generally performed when the crop is 4 inches (10 centimeters) tall and up to the height where equipment will still clear the crop. Interrow cultivation is most effective when weeds are not overly mature. Generally, cultivation is performed at depths less than 2 inches (5 centimeter) so that crop roots are not damaged and soil moisture is conserved.

Interrow cultivators can have modifications that allow soil to be ridged upon the crop row. Small weeds in the row can be buried. If the young crop is in danger of becoming buried by soil or weeds during cultivation, shields can be used on the cultivator. The goal is to maximize the cultivation area between the crop rows without damaging the crop.

Flame weeding

Flame weeding uses flaming propane burners to rupture the cells of the weeds, which usually die within 3 days. This technique is often used to supplement cultivation. If a soil is too wet to be cultivated before weeds become too large, flame weeding may be the only alternative. In row crops, flame weeding is used as a method of directed, within-row weed control (Figure 18-9). However, it can also be used as a broadcast technique, usually prior to crop emergence. When used after the crop has emerged, flame weeding is timed when the crop is at the correct stage of growth so that minimal damage occurs. Ideal conditions to flame are when the crop is bigger than the weeds. Flame weeding works best on dry, calm days. Producers must be well trained to avoid crop damage by flame weeding.



Kristine Moncada, University of Minnesota.

FIGURE 18-9
Inrow flame weeding. Weeds must be small and the soybean or corn crop must be at the correct stage for flaming to be effective and nondamaging to the crop.

Fertility

Soil fertility is comparable to weed control as an important factor limiting organic cropping systems. Organic producers must do considerable planning to provide nutrients to crops, as synthetic fertilizers used in conventional systems are prohibited. Green manures, animal manures, and compost manure are examples of commonly used organic fertilizers. Other soil amendments can be mineral based such as rock powders and lime, or organically based such as fish emulsions and kelp. Mineral fertilizers and some of the organic-based amendments are slow-acting and require long-range planning. A comparison of organic and conventional fertilizers is shown in Table 18-12.

Green Manures

A green manure is a crop that is incorporated into the soil to add organic matter, nitrogen, or other nutrients. Green manures can be legumes that fix nitrogen, or nonlegumes that scavenge nutrients. In organic systems, legumes like alfalfa and red clover, which are grown as components of rotations, are often used as green manures. Green manures can have dual functions; in addition to providing fertility, they also function as winter cover crops and forages (Figure 18-10). Hairy vetch and winter rye are examples of winter annuals that can be seeded in fall after crop harvest, provide winter cover, and be tilled the following spring. Legumes used as green manures can provide a significant source of nitrogen for the next crop; this is referred to as a **nitrogen credit** (Table 18-13). As opposed to manure or compost, green manure crops do not cause phosphorous accumulation in soils, and there is reduced leaching of nitrogen because nutrients are released slowly.

In addition to legumes, sorghum and Sudan grass are used for plowdown to add soil organic matter. These grasses can accumulate soil nitrogen and release it when they are incorporated.

TABLE 18-12

Differences between organic and conventional fertilizers.

Organic fertilizer	Conventional fertilizer
Naturally occurring with minimal processing	Manufactured or extracted with extensive processing
Nutrients are usually slow release	Nutrients are usually available immediately
Nutrients usually in low concentrations	Nutrients in high concentrations
Nutrients can be persistent in soil	Nutrients generally are not persistent in soil
Examples include manure, rock phosphates, and fish meal	Examples include ammonium sulfate, anhydrous ammonia, processed urea, and potassium chloride
Usually not more than one application per season	May require multiple applications within a single season
Many organic amendments will have less potential to cause environmental damage	Can have more potential to cause environmental damage if not used correctly



Craig Sheaffer, University of Minnesota.

FIGURE 18-10 Harvesting alfalfa. Alfalfa is used for forage as well as providing nitrogen in organic systems.

Livestock Manures

Manure is a valuable fertilizer resource on an organic farm. Its application can serve as a source of organic matter and plant nutrients (Figure 18-11). Livestock are inefficient in extracting nutrients from feed, and some of the nutrients in

TABLE 18-13

Nitrogen credit available to a subsequent corn crop in the first and second years following alfalfa or red clover plowing. *Adapted from O'Leary et al. (2008)*.

	Nitrogen credit			
	1st year		2nd year	
Previous crop	lb/ac	kg/ha	lb/ac	kg/ha
Harvested alfalfa				
4 or more plants/ft^2	150	168	75	84
2–3 plants/ft^2	100	112	50	56
1 or less plants/ft^2	40	45	0	0
Red clover	**75**	**84**	**35**	**39**


John Deere.

FIGURE 18-11
Manure spreader.

feed are excreted into the manure. Most common manures are beef, dairy, hog, chicken, and turkey (see Chapter 12). Properly managed manure can add plant nutrients and improve soil quality. Raw manure is high in nutrients, especially readily available nitrogen. Nitrogen is the main nutrient considered in application rate, but phosphorus and potassium should be monitored over time as they quickly build up in soil. Timing of application is also important, as raw manure is best applied to summer annual crops such as corn in the spring prior to planting. However, for crops that will be used for direct human consumption, spring application of raw manure may not be allowed (Table 18-14). Fall application is an option, but could lead to leaching and the risk of runoff if not properly applied.

TABLE 18-14

National Organic Program (NOP) manure and compost rules. *Adapted from the USDA NOP regulations (2010).*

1. No raw manure unless it is incorporated more than 120 days prior to harvest of crops for human consumption whose edible portion is in direct contact with the soil.
2. No raw manure unless it is incorporated more than 90 days prior to harvest for crops whose edible portion does not contact soil.
3. Compost can be applied at any time if produced according to rules.

TABLE 18-15

Advantages and disadvantages of compost compared to manure.

Advantages	Disadvantages
Slower release of nutrients	More expensive than manure
Spreads easier than manure	May be more difficult to find
Fewer weed seeds	Lower nutrient content
Less potential for runoff	Additional time and labor to produce compost
Fewer pathogens	Potential nutrient leaching during compost-making process
Less odors	
Fewer NOP restrictions on time of application	

Compost

Composting is the controlled decomposition of manure, crop residue, bedding, or other organic matter by microorganisms in the presence of oxygen. The goal of composting is to produce a nutrient-stable product. There are numerous advantages to composting compared to using raw manure that offset the storage and handling costs required to make the finished product (Table 18-15). Compost quality and nutrient content depend on the source materials of organic matter and the conditions under which the compost is made (Table 18-16).

Making quality compost depends on a good C:N (carbon:nitrogen) balance of the starting material (see Chapter 12). Usually animal bedding such as straw mixed with raw manure is an excellent base. The combined values of C:N ratios of the total starting materials must be in the range of 25:1 to 40:1. Finished compost will be half of these ratios. To produce compost approved for organic production, materials must be maintained at certain temperatures for defined time periods (Table 18-17). Other factors that are important in making compost are the correct levels of moisture and aeration (Figure 18-12).

TABLE 18-16

The nutrient content of different types of compost say chemical formula (16% P, 83% K). *Adapted from Rosen and Bierman (2005a).*

	Total N		P_2O_5		K_2O	
Compost type	lb/ton	kg/tonne	lb/ton	kg/tonne	lb/ton	kg/tonne
Poultry	17	9	39	20	23	12
Dairy	12	6	12	6	26	13
Mixed (poultry, dairy, swine)	11	6	11	6	10	5

TABLE 18-17

National Organic Program (NOP) rules for producing compost. *Adapted from the USDA NOP regulations (2010).*

FIRST

- Establish an initial C:N ratio between 25:1 and 40:1.

THEN

- Maintain a temperature of between 131°F and 170°F for 3 days using an in-vessel or static aerated pile system.

OR

- Maintain a temperature of between 131°F and 170°F for 15 days using a windrow composting system, during which period the materials must be turned a minimum of five times.



Ken Hammond, USDA-ARS.

FIGURE 18-12
Compost windrows being turned. Aeration and mixing are important in making proper compost.

Organic Livestock Practices

Like crop production, there also specific guidelines developed by the National Organic Program for organically produced meat and milk. Beef, dairy, and sheep must be raised following specific regulations:

- Access to pasture throughout the grazing season while forages are growing (Figure 18-13)
- Grazing animals must consume at least 30 percent of their diet's dry matter intake from pasture grazed during the grazing season. Grazing seasons must be a minimum of 120 days in length.
- No hormones to promote growth or milk production
- No antibiotics to treat diseases such as mastitis
- All feed fed to livestock must be certified organic.



Scott Bauer, USDA-ARS.

FIGURE 18-13
Organically raised beef cattle must have access to pasture each day throughout the grazing season. Thirty percent of their diet must come from grass.

Organic Milk from Grass-Fed Cows

Many organic dairy farmers feel that their animals are healthier on pastures and that having land in pastures provides better environmental stewardship than annual crop production. Milk produced on these farms is from cows that obtain all their nutrients from grass pastures during the grazing season (May to October) and from hay during the winter months. Cows have year-round access to pastures. During the grazing season, cattle are rotated among pastures and receive a new pasture each day. Most manure is deposited back onto pastures during grazing.

Some organic dairies have onsite processing plants that bottle their milk for sale at small, retail, on-farm stores or for sales at upscale supermarkets and natural-foods

coops. While it can be a significant investment for the farmers, processing and selling their own milk eliminates costs paid to middlemen and insulates the farm from fluctuations in organic milk prices. It also provides additional on-farm employment opportunities for the children.

The Rodale Institute: Pioneers in Organic Education and Research

The Rodale Institute in Kutztown, PA was founded in 1947 by J. I. Rodale to study the link between healthy soil, healthy food, and healthy people. Rodale began to advocate organic farming for crop production at a time when the development and use of synthetic pesticides and fertilizers were expanding. "Organics is not a fad," he wrote in 1954. "It has been a long-established practice—much more firmly grounded than the current chemical flair. Present agricultural practices are leading us downhill." (Rodale Institute, http://www.rodaleinstitute.org/). To inform and educate the general public and farmers, he founded the widely read organic magazine *Organic Farming and Gardening* (now known as *Organic Farming*). His son Robert and his family established what is now the Rodale Institute, and their children are today actively involved in achieving the mission of the institute.

Rodale Institute is committed to research in organic agriculture, advocating for policies that support farmers, and educating people about how organic is a healthy option for everyone. The Rodale Institute is actively involved in a number of projects. Currently, they are working with large- and small-sized farms to incorporate cover crops such as rye, barley, clover, or brassicas into rotations to protect the soil by capturing nitrogen, to control weed growth, to reduce erosion, and to keep soil organic matter intact, which makes the land more fertile.

Rodale Institute also has been conducting a 29-year-long farming system trial comparing conventional chemical agriculture with organic methods. The trial compares three systems for grain production: one conventional, one livestock-based organic, and one legume-based organic. The conventional system follows a 5-year rotation typical of many farms across the Midwest—corn-soybeans-corn-corn-soybeans—and receives fertilizer and pesticide applications according to the standard recommendations. The livestock-based organic system follows a 5-year rotation of corn-soybeans-corn silage-wheat-red clover/alfalfa hay, with cattle manure applied to corn. The legume-based organic system is structured around a 3-year rotation of hairy vetch/corn-rye/soybeans-wheat. The two organic systems receive no chemical inputs for fertility, weed, or pest control. Results from the trial have shown (Figure 18-14):

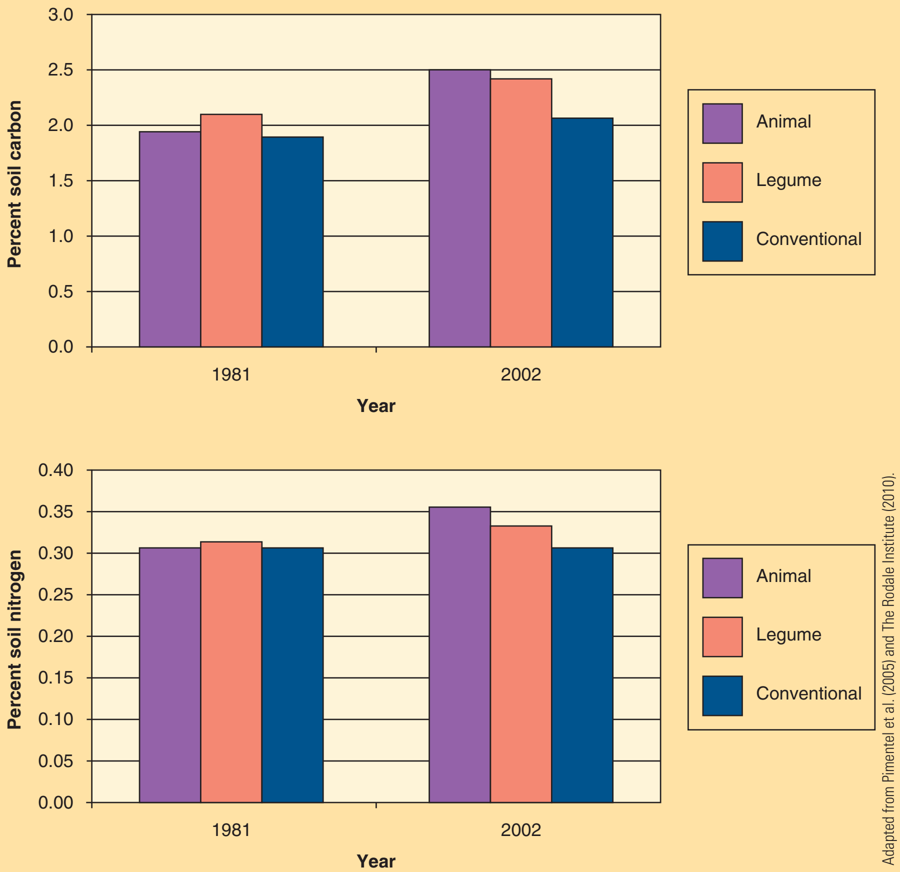


FIGURE 18-14 Percentage of soil carbon and soil nitrogen for the three systems in 1981 and 2002, The Rodale Institute Farming Systems Trial (Animal = organic animal-based system; Legume = organic legume-based system).

- Long-term corn and soybean yields are the same for the three systems, but under drought conditions, corn yields were 22 percent higher for the two organic systems compared with conventional corn. The superiority of the organic systems is attributed to their greater soil carbon and water-holding capacity compared to the conventional system.
- Energy inputs were about 30 percent greater for corn grown conventionally than when grown with the organic systems. This was attributed to use of fossil energy for production of synthetic fertilizer and pesticides. The soil nitrogen levels in the organic farming systems increased 8 to 15 percent. Nitrate leaching was about equivalent in the organic and conventional farming systems.

Review Questions

1. How does the USDA's National Organic Program (NOP) define organic agriculture?
2. What is organic certification and who does the certification?
3. What is the purpose of certification?
4. What are three of the requirements to be certified as an organic producer?
5. In terms of organic sales what are the two largest categories?
6. What are the most important organic crops?
7. What proportion of the total crop acreage (organic and conventional) does organic represent?
8. Weed control and soil fertilization have been identified as the most limiting factors in organic production. Identify and describe three approaches to manage weed control and soil fertility in an organic system.

Critical Thinking

1. What are several reasons why consumers purchase organic foods?
2. Have you considered consuming organic food? Why or why not?
3. Could organic agriculture meet the food needs of the United States?
4. Why are the yields of organic crops sometimes lower than those of conventional agriculture?
5. What is the level of organic crop production in your state?

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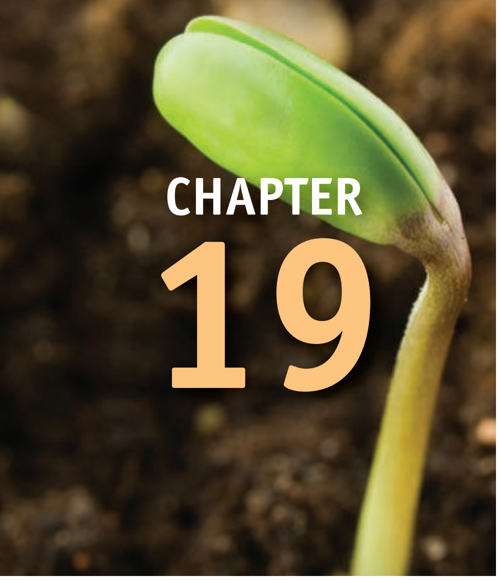
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CHAPTER 19



Crop Profiles: Grasses





Key Concepts

- Grasses are among the most important food crops in the world today.
- Cereals are grasses grown for edible seeds, whereas forage grasses are grown for their leaves and stems consumed by livestock.
- Corn is the most important crop in the United States, based on acreage and economic value.
- The six primary types of corn are pod, flint, pop, flour, sweet, and dent.
- Wheat is the most important cereal crop in the world and is made into bread and other products.
- Rice is the primary grain crop for over 50 percent of the world's population.
- Wild rice is the only grain crop that is native to the current United States and is used only for human food.
- Barley, oat, rye, and sorghum are additional important cereal crops.
- Cool-season forage grasses grow best in cool, moist climates and are used for hay, silage, and pasture.
- Warm-season grasses can be temperate or tropical, grow best at warm temperatures, and are used for grazing and haymaking.

Key Terms

amaranth
barley
buckwheat
celiac disease
cereal
cool-season grass
corn
Corn Belt
dent corn
ear
flint corn
flour corn
gluten
oat
pod corn
popcorn
pseudocereal
quinoa
rice
rye
silk
sorghum
spelt
sweet corn
tassel
triticale
warm-season grass
wheat
wild rice

Introduction

The grass family (Poaceae) is one of the largest and most important in the world. Grass crops were among the first domesticated by humans and were critical for development of early civilizations. **Cereals** are grasses grown for edible seeds. They are high in carbohydrates and low in protein (Table 19-1). Wheat, rice, corn, sorghum, and barley are among the most important food crops grown in the world (see Figure 2-6). In addition, billions of acres throughout the world are used for production of perennial forage grasses that are consumed by ruminant animals.

Corn (*Maize*)

Corn (*Zea mays*) and wild rice are the only cereal crops native to the Americas. Corn (maize) is thought to have originated in tropical south-central or southwestern Mexico. Archaeologists who excavated caves in mountains of the Techuacan Valley of southern Mexico found corn cobs dating from 8000 to 5000 BCE, representing both wild type and early domesticated corn. The ancestry of corn is unknown, but it may be related to teosinte (*Zea mexicana*) or *Tripsacum* wild grasses native to the area. Native Americans such as the Incas in Peru, the Mayas in Guatemala, and the Aztecs in Mexico used corn as a basic food source and conducted selection for larger kernel size, specific types of corn, and adaptability to specific environments. Scientists have discovered more than 300 distinct races of corn from Mexico, South America, Central America, and the Caribbean.

Native Americans traded corn throughout North and South America. They selected plants that could mature under the shorter growing season of more

TABLE 19-1

Nutritional composition of food grains based on a 100-gram sample. *USDA National Nutrient Database for Standard Reference (2010).*

Grain	% water	Calories	Protein, g	Fat, g	Carbohydrate, g	Fiber, g
Barley, pearled	10.1	352	9.9	1.2	77.7	15.6
Corn, yellow	10.3	362	8.1	3.6	76.9	7.3
Oats, rolled	8.2	389	16.9	6.9	66.3	10.6
Rice, brown	12.4	362	7.5	2.7	76.2	3.4
Wheat, winter	13.1	327	12.6	1.5	71.2	12.2
Triticale	10.5	336	13.1	2.1	72.1	14.0
Wild rice	7.8	357	14.7	1.1	74.9	6.2
Rye	11.0	335	14.8	2.5	69.8	14.6
Sorghum	9.2	339	11.3	3.3	74.6	6.3

northern latitudes. Archaeological evidence indicates that corn reached eastern North America about 250 BCE. Most likely, it was first used as a ceremonial crop and later became a food staple. Between 800 and 1100 CE, a shift in food production economies occurred, and maize became a dominant crop in North America.

When the Europeans arrived in the New World, Native Americans were growing corn extensively from southern Canada to Chile. Corn was often intercropped with beans and squash as one of the "three sisters." Columbus and later explorers brought corn to Spain, and its culture spread throughout Europe. As Europeans colonized the Americas, Native Americans shared their adapted corn types and their knowledge of cultural practices in growing corn. The survival of starving colonists in Virginia and New England in the 1600s was dependent on the generosity of the Native Americans (see Chapter 1). The legendary Pautuxet Native American Squanto taught the Pilgrims of the Plymouth Colony in Massachusetts to plant corn when the leaves on trees were the size of squirrel ears. The Pilgrims were also instructed to plant corn in hills, to use fish for fertilizer, and to hoe to control weeds.

The development of corn and human cultures has been interlinked. Corn cannot persist if humans do not collect and replant seeds. No wild forms of modern corn exist (Figure 19-1). Based on acreage and economic value, corn is the most important crop in the United States. Corn is grown in virtually every state in the continental United States, but acreage and production is concentrated in the historic **Corn Belt** states of Iowa, Illinois, Minnesota, Indiana, and Ohio. Nebraska and South Dakota also have significant corn acreage (Table 19-2). In 2009 almost 80 million acres (32 million hectares) of corn were harvested in the United States, with a total value of $49 billion.

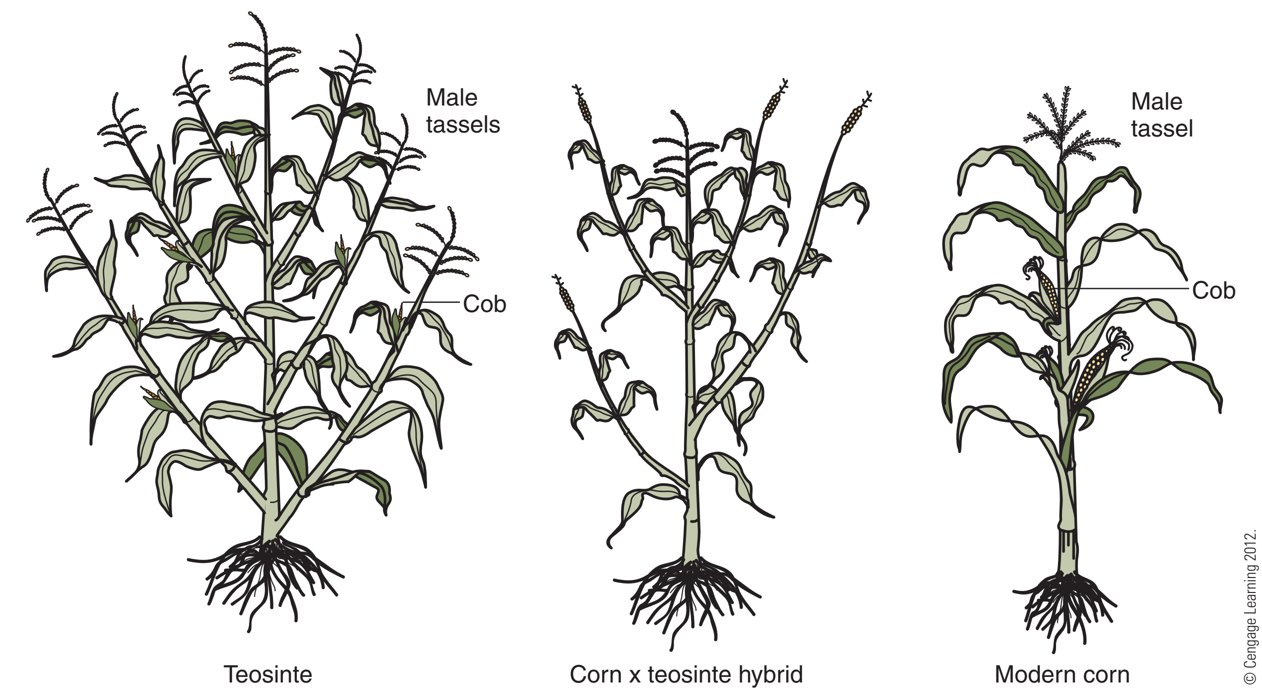


FIGURE 19-1 Modern corn and its possible ancestors.

TABLE 19-2

Acreage and yield of the top-producing states of corn in 2009. *Adapted from USDA-NASS (2010).*

	Total area		Average yield	
State	in acres	in hectares	bu/acre	kg/hectare
Iowa	13,400,000	5,422,788	182	11,424
Illinois	11,800,000	4,775,291	174	10,922
Nebraska	8,850,000	3,581,468	178	11,173
Minnesota	7,150,000	2,893,502	174	10,922
Indiana	5,460,000	2,209,584	171	10,733
South Dakota	4,680,000	1,893,929	151	9478
Kansas	3,860,000	1,562,087	155	9729
U.S. total	79,590,000	32,208,930	165	10,338

Description and Adaptation

Corn is a tall-growing annual grass with most commercial, yellow dent-type hybrids growing from 10 to 15 feet (3–4.6 meters; Figure 19-2). Corn is unique compared to most other grasses. It is moneocious, with separate male and female flowers on the same plant. The male flowers (the **tassel**) are borne at the terminal portion of the plant and one or more female parts (the **ear**) are borne in leaf axils. The corn **silk**, which extends from the corn husk, is the stigma and style. The typical corn stalk is 1–2 inches (2.5–5 centimeters) in diameter with distinct nodes and internodes. The typical commercial dent corn has from 10 to 15 nodes with leaves alternately attached to the stalk. When mature, corn has two primary types of root systems. Brace roots, a type of aerial roots, are above ground and arise at nodes on the bottom of stems in support of the plant (see Chapter 7), but roots arising from the seed and crown are the primary system for providing water and nutrients.

Corn is a short-day crop of tropical origin and is intolerant of air temperatures less than 32°F (0°C). In the United States, corn is grown as an annual with flowering and seed production during the summer months. Through plant breeding, it has adapted to the growing seasons of many more northern temperate regions. Hybrids have been selected for maturation during frost-free periods of 70–180 days. Corn seed germinates at temperatures above 50°F (10°C), and corn grows best when average daily temperatures average about 70°F (21°C). The average amount of water required to produce a corn crop in the Midwest is from 20–40 inches (51–102 centimeters) per year.

Corn Types

Although there is much variation in corn grain types, we will discuss six primary types of corn with historical and current significance: pod, flint, pop, flour, sweet, and dent (Figure 19-3). These divisions are based mostly on the patterns of

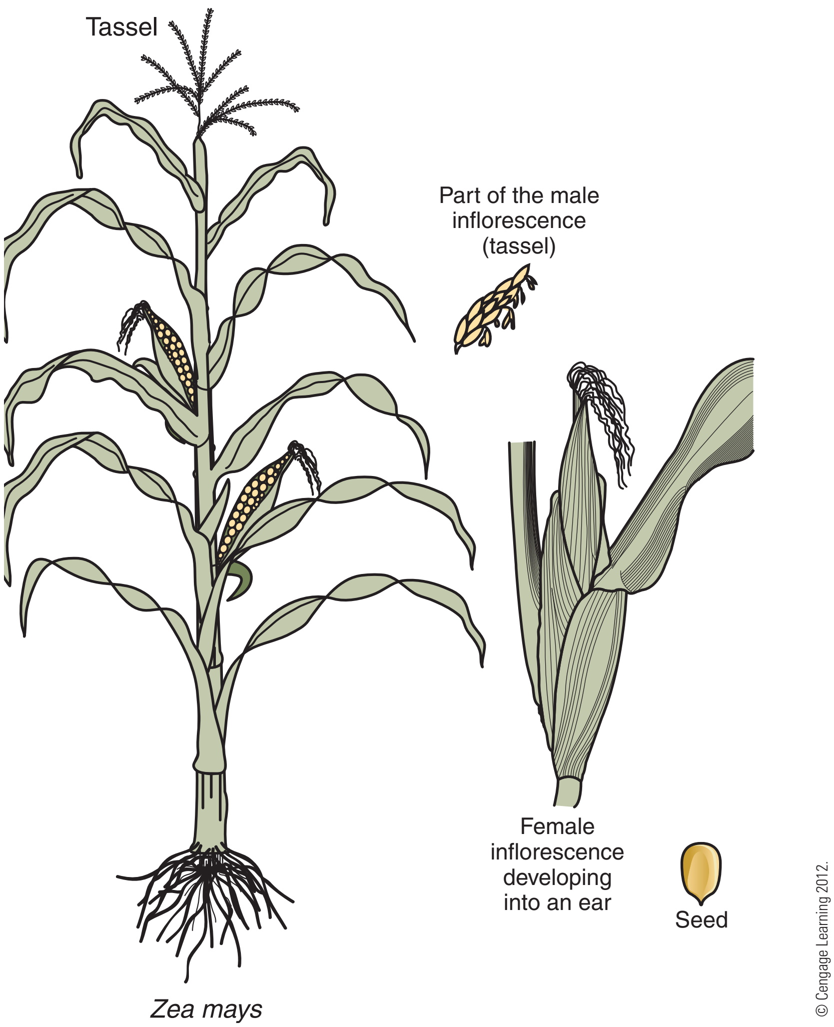


FIGURE 19-2
A modern corn plant.

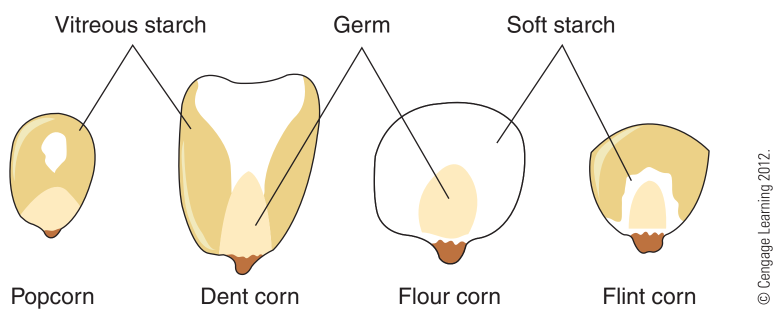


FIGURE 19-3
Four of the six types of corn based on kernel characteristics. Flint and popcorn have a hard starch layer surrounding the soft endosperm. Dent corn has hard starch on the sides and a soft starch in the middle that shrinks when it dries. Flour corn is completely soft starch and is oval when it dries.

endosperm composition in the kernel. The earliest corn was hard-seeded flint and pod types. Native Americans likely selected flour corn because it could be easily ground. Corn that Native Americans provided to colonists was mostly multicolored flint and flour types.

- **Flint corn** has a small, starchy endosperm enclosed in a thick layer of hard endosperm called *horny endosperm*. The horny endosperm makes the corn resistant to insects and fungi and allows for better storage than flour types. Flint corn was the first corn adapted to northern temperate regions and was the predominant corn that Native Americans grew prior to European settlement. Little flint corn is currently produced in the United States for commercial purposes, but it is used as an ornamental.
- **Flour corn** has soft starch throughout, with no horny (vitreous) endosperm and little or no dent. Flour corns were widely used in native cultures in the Southwest because of ease of grinding. Today, they are used for production of tortilla and corn chip food products.
- **Popcorn** has endosperm characteristics similar to flint corn except the kernel is smaller. The kernels can be either pointed or round, and most are either white or yellow. Though most corn types with some soft starch will pop, the expansion properties of popcorn starch are unique. For optimum popping, kernel moisture content should be 14 percent. Popcorn is considered mostly a snack food, but colonists consumed it as a breakfast food.
- **Sweet corn** has a high sugar content and no starch. Sweet corn kernels have a translucent, hard, and shriveled appearance when dried. Sweet corn likely was selected from flint corn or popcorn plants that lost their ability to produce starch.
- **Pod corn** has each kernel enclosed in a pod or husk, possibly like primitive corn types and many other species in the grass family. It is primarily used for ornamental purposes.
- **Dent corn** has a hard, horny endosperm at the sides and back of the kernels. A depression (the dent) forms at the top of the kernel as the starch endosperm dries and shrinks. Dent corn is the most widely grown of the corn types. Dent corns likely originally developed through crossing of flour and flint corn. Because corn is open-pollinated, repeated crossing and selection by farmers occurred. Today, plant breeders continue to select dent corn for additional traits such as kernel composition and adaptability to unique environments.
- Special-purpose corns have been developed with modified starch, protein, oil, and other properties. These include waxy, high-lysine, high-amylose, and high-fermentable (for ethanol production) corns. Corn hybrids are also being developed that have traits such as improved amino acid profile (e.g., greater methionine content) and greater oil content. White corn resembles modern yellow corns but without the carotene content of the yellow corn. It is used largely for production of tortillas, taco shells, meal, and hominy. Waxy corn has kernels that appear waxy because they contain a high proportion of branched amylopectin starch.
- Ornamental or Indian corns have been selected for variable kernel-color characteristics. They can be selected from any of the major corn types, although they are often flint or flour corns.

Hybrid Corn

Corn is a naturally cross-pollinated plant with considerable genetic mixing occurring within and among populations. Early Native Americans and later farmer seedsmen selected seeds from plants that had desirable traits such as large, nonshattering ears. Other selection for shorter growing season and stressful environments was important to expand corn production. For example, 'Reid Yellow Dent' was selected for yield as well as ear characteristics near Peoria, Illinois, beginning in the mid-1850s. It was the dominant corn in the Corn Belt for 50 years. For the northern Corn Belt, 'Minnesota 13' was selected in St. Paul in the 1890s for its early maturity and adaptability to a short growing season.

Most corn that is now grown in the United States is the product of hybridizing. Before hybridizing, most corn was open-pollinated. Since 1927, when the first hybrids were sold by the Pioneer Hi-Bred Corn Company, corn grain yields have dramatically increased. Acreage planted to corn hybrids has increased from less than 1 percent in 1933 to nearly 100 percent in 1960. In the process of developing hybrids, unique inbred lines with increased genetic homogeneity are developed by self-pollinating selected plants for multiple generations (see Chapter 9). The inbred lines are then hybridized to produce single crosses. Crossing of inbreds mixes genes and causes heterosis (hybrid vigor). The first marketed hybrids were double crosses that were produced by the crossing of two single-cross plants. Currently, most marketed corn hybrids are single crosses.

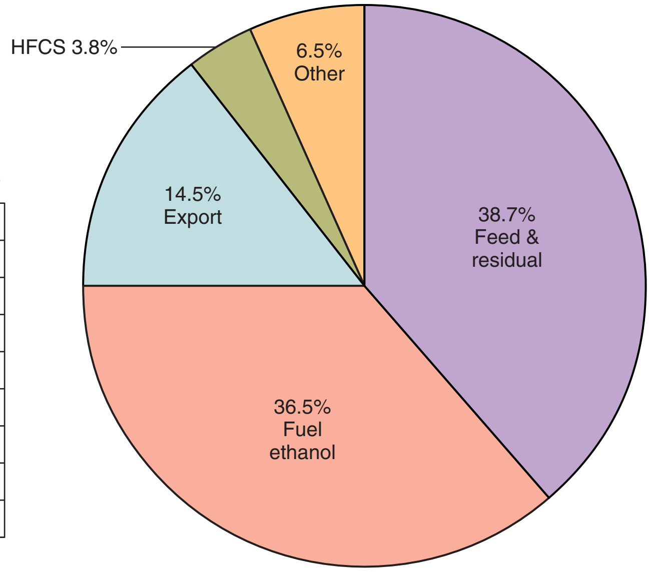
Use

Corn grain has long been valued as an important source of energy for human and livestock diets (Figure 19-4). As a food, corn grain is a good source of carbohydrates (60% starch), lipids (5% oil), and proteins. However, the protein content is relatively low (7–8%), and it is deficient in the essential amino acids lysine and tryptophan.

Americans consume corn in many ways. Corn may be consumed directly as corn on the cob, as processed corn products such as corn flakes, or as a sweetener in candy or soda. It is also indirectly consumed because it is a key ingredient in the feed of cattle, poultry, and swine.

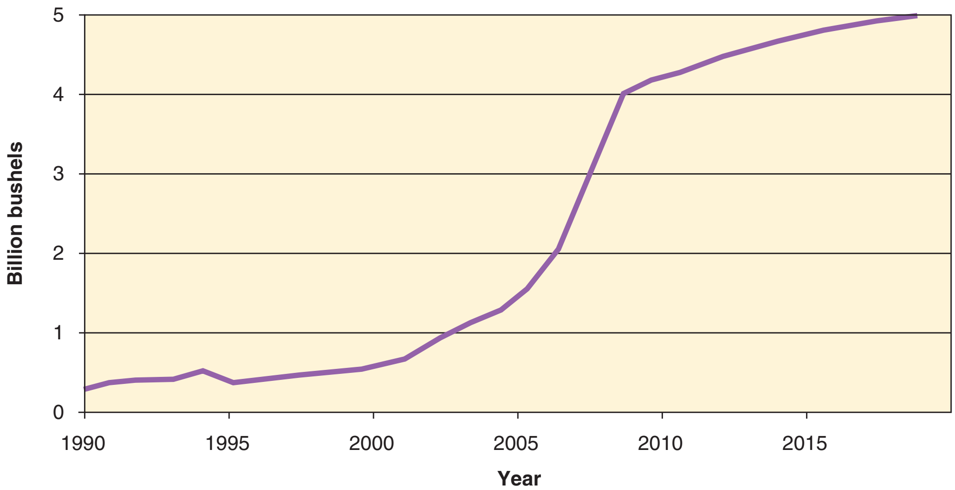
The starch in corn grain has historically been fermented by yeast to produce ethyl alcohol (ethanol; CH_3CH_2OH). Ethanol is an intoxicating liquid for people, but it also has many other industrial uses. Currently, corn-based ethanol is used as a replacement for gasoline produced from fossil fuels. One bushel of corn can produce at least 2.8 gallons (10.6 liters) of ethanol and about 18 pounds (8 kilograms) of grain by-product. The use of corn for ethanol production will likely increase over time (Figure 19-5). E85 fuel, made from 85 percent ethyl alcohol and 15 percent gasoline, is available on a limited scale, and automakers are producing E85-capable vehicles. See Chapter 5 for more information on biofuels. Distillers grains, which are the corn residue from ethanol production, are sold for low-cost livestock feed. Other industrial products of corn include biodegradable plastics, packing materials, glues, and lubricants. With greater use of corn for ethanol production, the availability of corn for livestock feed and human foods may decrease. Food costs in the United States will likely increase as a result.

	Million bushels
Feed & residual	5,200
Export	1,950
Fuel ethanol	4,900
High-fructose corn syrup	515
Starch	250
Sweeteners	260
Cereal/other	197
Beverage alcohol	135
Seed	23



USDA-ERS (2011).

FIGURE 19-4 U.S. corn usage in 2010. *HFCS* stands for high fructose corn syrup. 1 million bushels = 25,400,000 kilograms.



USDA-ERS (2009).

FIGURE 19-5 Corn used as ethanol in fuel. The use of corn grain for ethanol production will increase according to USDA projections. The total percentage of domestic corn used for ethanol is now more than 20 percent. 1 billion bushels = 25 billion kilograms.

Corn is also grown as a silage crop for livestock feeding. High-quality corn silage is made by chopping and storing the whole plant in an anaerobic environment, where fermentation lowers the pH and preserves the material. A specialized storage structure such as a silo is used. In the United States, more than 10 million acres (4 million hectares) of corn are grown for silage, with an average yield of 20 tons/acre (45 tonnes/hectare).

The National Corn Growers Association

The National Corn Growers Association is a dues-based membership organization founded in 1957. Today the organization has over 35,000 members across the corn-growing regions of the United States and is headquartered in St. Louis, Missouri. Through advocacy, lobbying, and national programs, the Corn Growers Association has represented the interests of farmers and the corn industry. The Corn Growers Association also works with affiliated state branches of the organization.

The National Corn Growers Association has successfully advocated for a variety of different initiatives to increase the use of corn by consumers and industry. Some of the most notable include increasing high fructose corn syrup use by the beverage and processed foods industry, building acceptance for ethanol production and higher blends of ethanol in motor vehicle fuel, increasing the research and development towards discovering new commercial uses for corn, and working to open new international markets to American corn. For more information, visit the National Corn Growers Association at <http://www.ncga.com>.

Wheat

Wheat originated as a product of natural crossing of plants in the Fertile Crescent nearly 10,000 years ago. Additional genetic and morphological changes occurred in the centuries thereafter. It is thought that the first wheats resulted from the interbreeding of Eikorn wheat (*Triticum monococcum*) and a goat grass (*Aegilops* sp.). This resulted in Emmer wheat (*Triticum turgidum*), which is the precursor for the durum wheat (*Triticum turgidum* var. *durum*) that is grown today. Additional crossing of Emmer wheat with wild goat grass resulted in the precursors of bread wheat (*Triticum aestivum*). Originally, people from early civilizations felt wheat was less important than barley. But wheat ended up replacing barley because it is more easily extracted from the leaf-like hulls and can be made into bread. Spanish explorers introduced wheat into North America in the 1500s, and it was grown in the New England colonies in the early 1600s. In the early 1800s, Pennsylvania, New York, and Virginia were known as the bread basket of the colonies, producing more than 60 percent of the new nation's crop. Its culture spread westward as the country was settled.

Wheat is called *the staff of life* because of its importance in human nutrition and breadmaking. Wheat is the most important grain crop in the world. In the United States, it is the third-leading grain crop. Total wheat acreage is greatest in Kansas, North Dakota, Montana, Washington, and South Dakota.

Increased disease resistance through plant breeding was essential for the development of wheat as a major world crop. Wheat stem and leaf rust caused by fungi (*Puccinia* spp.) have historically had devastating effects on wheat yields. The success of the Green Revolution was in large part due to the development of disease-resistant wheat varieties.

Description and Adaptation

Wheat is an annual grass plant (Figures 19-6 and 19-7). Wheat develops a crown following seeding and produces a fibrous root system. Multiple stems (tillers) arise from the crown and are terminated by an inflorescence containing flowers.

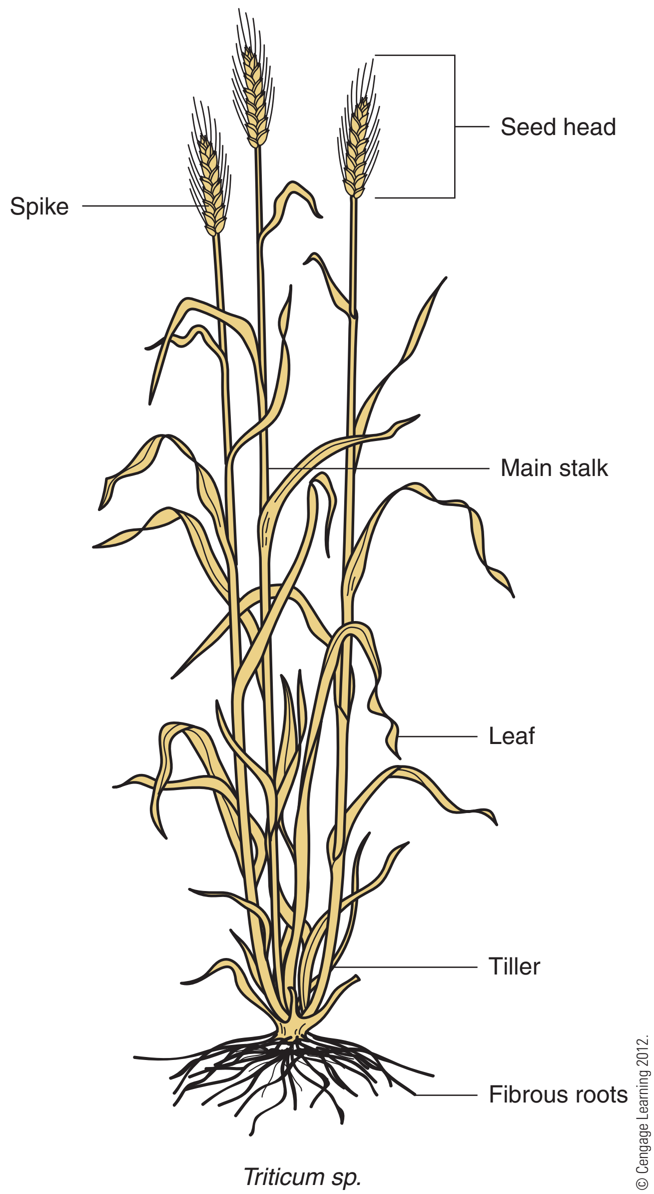


FIGURE 19-6
A wheat plant showing the multiple tillers and grain heads.



FIGURE 19-7
Mature wheat standing in the field. Awns may or may not be attached to the wheat floret depending on the variety.

Tiller number depends on plant population, but typically will be from three to five per plant. The inflorescence of wheat is a long, cylindrical spike containing about 30 grains. Wheat grains are easily separated from their vegetative flower parts (or chaff) during threshing.

Wheat is adapted to temperate climates with moderate temperatures and a average rainfall from 10 to 20 inches (25–51 centimeters). High temperatures and humidity, especially during flowering and grain development, favor the development of diseases. There are spring and winter wheats. Winter wheat is planted in the early fall, several months before the soil freezes, and it matures the following summer. Winter wheat is cold tolerant and must be subjected to a cold period during the winter (vernalization) to induce flowering in the spring. Winter wheat

acreage is largest in Kansas, with nearly 9 million acres (3.6 million hectares) planted. Oklahoma, Texas, Montana, and Nebraska also grow more than a million acres (400,000 hectares) of winter wheat (Table 19-3). In southern areas, winter wheat can be grazed by livestock in the fall or winter and then harvested for grain in the spring. Spring wheats, planted in the spring (as the name suggests), are grown in northern latitudes such as the Dakotas, Montana, Minnesota, and the plains of Saskatchewan and Manitoba, Canada. Wheat is a long-day plant and flowers in response to long days in the spring of the year.

Market Classes of Wheat

Wheat is traded and marketed in six classes that are based on their grain composition and kernel characteristics (Table 19-4). The hard versus soft wheat designation is based on the hardness of the kernel. Hard kernels have greater protein content.

TABLE 19-3

Acreage and yield of the top-producing states of spring, durum, and winter wheat in 2009. *Adapted from USDA-NASS (2010).*

		Total area		Yield	
Wheat	State	in acres	in hectares	bu/acre	kg/hectare
Spring wheat	North Dakota	6,300,000	2,549,520	46	3094
	Montana	2,350,000	951,011	30	2018
	Minnesota	1,550,000	627,263	53	3,564
	South Dakota	1,470,000	594,888	44	2959
	U.S. total	12,955,000	5,242,702	45	3033
Durum wheat	North Dakota	1,570,000	635,356	39	2623
	Montana	535,000	216,507	31	2085
	California	170,000	68,797	100	6725
	Arizona	124,000	50,181	100	6725
	U.S. total	2,428,000	982,577	45	3020
Winter wheat	Kansas	8,800,000	3,561,234	42	2825
	Oklahoma	3,500,000	1,416,400	22	1480
	Colorado	2,450,000	991,480	40	2690
	Texas	2,450,000	991,480	25	1681
	Montana	2,420,000	979,339	37	2488
	U.S. total	34,485,000	13,955,584	44	2972

TABLE 19-4

Market classes of wheat in the United States.

HARD RED WINTER WHEAT

- Protein content: 12–13%
- High gluten content
- Largest production class
- Used for making bread, rolls, and all-purpose flour
- Grown in the Great Plains
- Grown as a winter annual

HARD RED SPRING WHEAT

- Protein content: 14–15%
- High gluten content
- Used for making bread
- Grown in the Midwest
- Grown as a summer annual

SOFT RED WINTER WHEAT

- Low protein content: 10–12%
- Low gluten content
- Used for pastries, cakes, and crackers
- Grown in the eastern United States
- Grown as a winter annual

SOFT WHITE WHEAT

- Protein content: 10–13%
- Low gluten content
- Used for breakfast foods, cakes, pastries, and crackers
- Grown in Washington, Oregon, California, Michigan, and New York
- Grown as a winter annual

HARD WHITE WHEAT

- Protein content: 11–14%
- High gluten content
- Used for breads, pizza crusts, flatbreads, tortillas, and Asian noodles
- Grown in Kansas, Colorado, Nebraska, Oklahoma, and Texas
- Grown as a winter annual

DURUM WHEAT

- Highest protein content: 15–16%
- Low gluten content
- Used for making semolina for macaroni, spaghetti, and couscous
- Grown in North Dakota
- Grown as a summer annual



Breadmaking

The preeminence of wheat among grains is because of its ability to be made into bread and other products. Compared to other prepared foods, bread can be stored longer and remains more palatable than other grains. The ingredients for most breads are wheat flour, sugar, water, salt, and yeast. The rising properties of bread depend on the presence of **gluten**, a compound protein that is found in certain types of wheat. Gluten is a compound of two proteins: gliadin and glutenin. Gluten binds with the starch of the flour and forms a spongy matrix that traps carbon dioxide, which is released following the fermentation of sugars by yeast.

During the early stages of baking, gases cause the bread to rise until a temperature is reached at which the yeast is killed and the dough hardens around the gas. In modern breadmaking, precise amounts of gluten from wheat are mixed with flour of wheat and other grains.

There are many different types of flour used in breadmaking and other baking, including the following:

- **All-purpose flour.** This is made from either only hard wheats or a combination of soft and hard wheats. It can be used for breads, cakes, cookies, and pastries.
- **White flour.** This is refined whole wheat flour. Refining is the process of removing the bran and germs that contain nutrients.
- **Bleached enriched flour.** This flour is exposed to bleaching agents such as chlorine gas to condition the gluten and whiten the flour. The bleaching agent evaporates and does not contaminate the flour. With enriching, some nutrients are added back to the flour.
- **Self-rising flour.** This flour is an all-purpose flour with salt and a leavening agent (baking powder) added.
- **Cake and pastry flour.** These flours are made from white wheats and are low in protein and gluten, and they are used in cakes and cookies.
- **Bread flour.** This is made only from hard wheat. It has a high protein and gluten content and is used for making yeast-type breads.
- **Gluten flour.** This is flour that is enhanced with gluten. It can be added to other flours to enhance bread quality.
- **Whole wheat flour.** It is made from processing the whole grain including the endosperm and germ. It is typically darker and has higher fiber and nutrient content than refined grains.

Some individuals have a hereditary intolerance of gluten called **celiac disease**. For those afflicted, ingestion of gluten results in damage to the

small intestine. The symptoms are nausea, diarrhea, and overall distress of the digestive system. Chronic symptoms include weight loss and malnutrition. Because small quantities of gluten are found in most small grains, avoiding gluten consumption is challenging. To avoid the symptoms, consumption of a gluten-free diet is required. Individuals must eliminate all wheat, rye, barley, and triticale products from their diets. Grains that are allowed include rice, corn, sorghum, quinoa, millet, buckwheat, amaranth, teff, and flax.

Related Species

Spelt (*Triticum aestivum* var. *spelta*) is a subspecies of wheat that has been grown in the United States only since the beginning of the twentieth century. The kernels remain in the lemma and palea after threshing. It is an alternative feed grain to oat or barley on infertile soils. Spelt is a relatively low-gluten wheat.

Triticale (*Triticale hexaploide*) is a human-developed annual grain resulting from a cross between wheat and rye. It was developed because of its potential for higher grain yields and grain quality than either wheat or rye. Triticale is not widely grown. It has high grain protein content but lacks the breadmaking qualities of wheat. It also lacks the winter hardiness of rye.

Buckwheat (*Fagopyrum sagittatum*) belongs to the Polygonaceae family and is not genetically related to wheat, despite its name. It is an herbaceous dicot with a central, branched stem growing up to 3 feet (0.9 meter) tall. It is a cool-season annual. The fruit of buckwheat is a hulled achene rather than a grain. Buckwheat was domesticated in China and was an important human food source. It also was an important crop during the settlement of the United States, because it produces better yields than the other small grains and corn on infertile and poorly drained soils. It also grows rapidly and is competitive against weeds. Organic producers use it as a green manure crop. Additionally, buckwheat is an effective nutrient scavenger (meaning it can take up excess nutrients) and can enhance nutrient availability in a soil. It is one of the best crops for bees in honey production. Buckwheat is used for both human and animal feed. Buckwheat pancakes are a popular use for buckwheat flour.

Rice

Rice (*Orza sativa*) is one of the oldest cultivated grains. Types of rice originated in China, India, and Indonesia. Colonists initially brought rice to South Carolina in about 1690, and it became an important crop in southeastern United States. Rice is a primary grain crop for more than 50 percent of the world's population. Rice consumption in the United States has steadily increased, and Americans consume about 20 pounds (9 kilograms) per capita of rice per year. The world's largest

production occurs in Asia, with the majority of the crop grown in China, India, Indonesia, and Thailand. In the United States, nearly half of the rice is grown in Arkansas (1.5 million acres [0.6 million hectare]). California, Louisiana, Texas, Mississippi, and Missouri also each grow more than 100,000 acres (40,500 hectares).

Description and Adaptation

The rice plant is a multi-tillered grass that grows to an average height of about 2–6 feet (0.6–1.8 meters; Figure 19-8). It has a panicle inflorescence, and the lemma and palea adhere to the grain when mature. Rice is the only grain adapted to moisture-induced anaerobic conditions and is typically grown in flooded paddies or in floodwaters. The stem and root contain large air spaces that allow for air diffusion throughout the plant. Rice leaves are able to float on water because

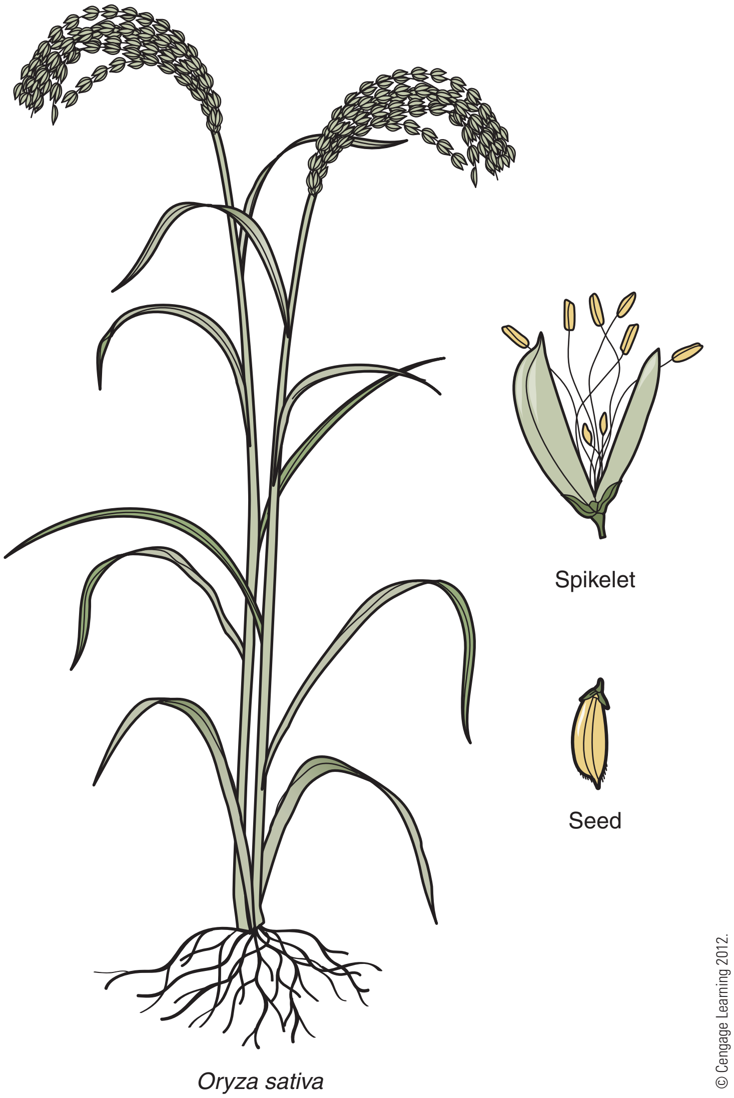


FIGURE 19-8
Rice plant.

of the air spaces. Rice can grow under dryland or upland conditions, but it is most productive when grown submerged in water or frequently irrigated. Upland rice is most often grown in humid, tropic regions that receive a high frequency and amount of rainfall. Rice is a warm-season, short-day species.

Rice is usually grown as an annual crop, but in the humid tropics, farmers can harvest a second, or ratoon, crop from the regrowth of the initial planting. Rice cultivation in most of the developing world is still performed by hand, which is very labor intensive, whereas production in the United States is highly mechanized, and airplanes are frequently used for sowing the seed and applying chemicals.

Two major subspecies (types) of rice are widely grown. The indica types are adapted to tropical climates and produce a long grain (~0.3 inch [8 millimeters]) that is not sticky when cooked. The japonica types are adapted to cooler temperatures in temperate regions and have a shorter grain (~0.2 inch [6 millimeters]) that is sticky when cooked. In the United States, japonica types are grown in California, whereas indica types are grown in southern states (Figure 19-9). Jasmine and basmati rice, as well as specialty aromatic rice, are produced mainly in India and Thailand.



Keith Weller, USDA-ARS.

FIGURE 19-9
Indica-type rice grown in the southern United States. It is a long-grain rice.

Use

Rice is primarily consumed as human food. The grain can also be ground into flour and fermented to produce sake, an alcoholic beverage. Rice must be milled before consumption because vegetative flower parts (lemma and palea) adhere to the ripe grain. Removal of these leaf-like coatings produces brown rice. Rice consumed by most Americans is called polished (or white) rice. It is produced by removal of the bran and germ that are a rich source of vitamins and fiber. After cooking, rice retains its shape better than other grains. It also has a soft texture and readily absorbs flavors from spices, soy sauce, or meat broths.

Wild Rice

Wild rice (*Zizania aquatica*) is the only grain crop that is native to the current United States. Native Americans in the Great Lakes region harvested it from lakes and rivers in the fall, and it was an important nutrient source for surviving severe winters. Native Americans called wild rice *manomin*, meaning the good berry. Wild rice is a minor crop in the United States that is gaining in popularity. It has a unique taste and is used only for human food.

Description and Adaptation

Wild rice is a summer-annual, cool-season plant adapted to northern latitudes (Figure 19-10). Plants are typically 5–6 feet (1.5–1.8 meters) tall with as many as 50 stems or tillers per plant. Like *Oryza sativa*, wild rice is adapted to being submerged underwater. It has a hollow stem, air-filled spongy roots, and floating leaves. Wild rice is a monoecious plant with flowers in a branching panicle. Female (pistillate) flowers are at the top of the inflorescence and male (staminate) flowers on the bottom (Figure 19-11). Cross-pollination among plants usually occurs because female flowers of a plant mature before male flowers. Natural stands of wild rice have plants that flower at different times and, within a plant, the seeds on any tiller will mature at different times. At maturation, wild rice plants naturally shatter and drop their seeds into water. The traits of lack of uniform maturity and shattering are important for wild rice survival in natural stands, but undesirable for commercial cultivation. Development of varieties with shatter resistance was responsible for the development of commercially produced wild rice. In natural stands, seed of wild rice is submerged over the winter to germinate in the spring.

Wild rice is a cool-season annual grass with tolerance of wet soil. Most wild rice is produced in flooded paddies that are drained before harvest (Figure 19-12). Minnesota and California are the leading states for commercial production. In total, about 30,000 acres (12,000 hectares) are grown, with a yield of about 1500 pounds/acre (272 kilograms/hectare). Native Americans still use canoes to harvest wild rice from natural stands in lakes and rivers.



FIGURE 19-10
Wild rice.



David L. Hansen, University of Minnesota.

FIGURE 19-11
Wild rice plants. Note the distinctive inflorescences.



David L. Hansen, University of Minnesota.

FIGURE 19-12
Wild rice paddy (top) and wild rice harvesting (bottom).

Use

Wild rice grain is high in protein (14%) and carbohydrates (74%), and it is low in oil. Linoleic (omega 6) and linolenic acid (omega 3) content of the grain is high. When the grain supply was limited, wild rice was considered a delicacy. It is now widely available and marketed in a variety of ways, including prepared soups and dried, packaged mixes.

Mature wild rice seed is covered with vegetative flower parts (lemma and palea), so processing is required before consumption. Steps in the process include fermentation (curing) to degrade the hull and impart the flavor into the grain, drying, dehulling, and scarification (scratching) of the impermeable layer on the exterior of the seed. Scarification reduces the cooking time of the grain.

Barley

Barley (*Hordeum vulgare*) is one of the oldest cultivated crops, having been domesticated in the Fertile Crescent region about 10,000 years ago. The Egyptian, Greek, and Roman civilizations used barley in breads, porridges, and soup. In addition, barley and other grains have been used to make beer as long as 6000 years ago. The early development of barley as a grain crop is likely due to its tolerance of drought and frost, as well as saline soils. It also matures somewhat earlier than other small grains. The economic importance of barley as a grain crop has decreased in recent years. North Dakota, Idaho, and Montana produce about 70 percent of the barley in the United States.

Description and Adaptation

The barley plant resembles many of the other small grains in terms of vegetative characteristics in that it develops a crown with multiple tillers (Figure 19-13). Its flowering inflorescence is a cylindrical spike with spikelets in either two or six rows (Figure 19-14). The lemma and palea (or hull) are fused to the seed. The lemma has a long awn. For human consumption, the seed coatings must be removed in a process called pearling. Barley is a cool-season annual and is known for its relatively greater tolerance of drought and salinity than other small grains. Spring and winter barley are grown.

Use

Barley grain is used mostly for livestock feed. The brewery industry uses about one-third of the crop. Barley has inadequate gluten levels for making raised bread. The varieties grown for malting have been selected for grain chemical characteristics including amylase activity and for low grain protein.

Barley is the most important grain for making quality beer (Figure 19-15). Beer can be produced from fermentation of many types of starch, but barley produces a distinct taste because the lemma and palea seed coating stay attached to



FIGURE 19-13
Two-row barley plant.

the grain during malting and add some flavor. There are several steps in the production of beer. These include the following:

1. **Malt preparation.** The dried grain is moistened and germinated. Within the germinating grains, enzymes convert the starch to sugars. *Malt* is a shorthand term for the maltose sugar that is produced. The germinated grain is then roasted and crushed to produce malt powder. Malt powder is the substrate for fermentation, or it can be used for making products such as malted milk balls and malted milk shakes.



FIGURE 19-14
Six-row and two-row barley.

2. **Mash production.** The malt powder is then mixed with the starch of other grains such as rice, wheat, or corn. The malt enzymes then convert all these starches to sugars. After the conversion is completed, the mixture is filtered and the liquid, called the *wort*, is saved.
3. **Mixing and brewing.** The wort is mixed with hops or other flavoring ingredients and then cooked or brewed. Hops add flavor to beer and help retain the foamy head of beer longer.
4. **Fermentation.** The cooked wort is cooled and yeast is added. The yeast converts sugars to ethanol and carbon dioxide. Different types of yeast produce beer with distinct characteristics. Bottom-fermenting yeasts produce lagers, whereas top-fermenting yeasts produce ales.
5. **Aging.** Following fermentation, the beer is aged for several weeks, often with beechwood chips to provide flavoring. During aging, additional fermentation and natural carbonation can be stimulated by adding a small amount of wort and yeast.
6. **Filtering, pasteurizing, and carbonation.** The final steps before packaging involve filtering of the aged beer to remove any impurities or microorganisms. Bottled and canned beers are usually pasteurized, whereas draft beers are only filtered. Many beers are also carbonated before canning or bottling. The alcoholic content of beer averages about 5 percent, but it can range from 3 to 12 percent depending on the type.

   Some different types of beer include the following:

- **Ale.** A special top-fermenting yeast produces ale. It is made from only barley malt.
- **Lager.** These beers are the predominant types made in the United States. They are produced by bottom-fermenting yeast and are made from starch from barley, corn, and rice.



David L. Hansen, University of Minnesota.

FIGURE 19-15
Barley is an important component of beer.

- **Light beer.** This beer has fewer calories than normal beer. It is produced using a longer period of sugar fermentation that lowers the calories and reduces the alcohol content somewhat.
- **Pilsner.** This beer is a lager beer brewed with a strong hop component.

Oat

Oat (*Avena sativa*) was domesticated later than many other small grains and may have initially been a weed in cultivated wheat or barley. The grain is relatively high in fiber and protein. Oat has historically been valued as a horse feed. North Dakota, Minnesota, and Wisconsin are the leading states for oat production, with many other northern states having small oat acreages.

Description and Adaptation

Oat is an annual grass that grows to a height of about 3 feet (1 meter) (Figure 19-16). Plants have from three to eight tillers. The inflorescence is a many-branched panicle, and the individual spikelets have up to seven florets with three to four usually producing grain (Figure 19-17). After harvest, the lemma and palea adhere to the grain and are dehulled for human consumption. Oat is best adapted to moist, temperate climates. It is typically planted in early spring and grown as a summer annual. Winter oat varieties are also grown.



FIGURE 19-16
A single tiller of an oat plant.



FIGURE 19-17
The inflorescence of oat.

Use

Although its acreage has declined because of the reduced need to feed the horses and mules that once powered agriculture, oat is still valued as a horse feed because the grain is palatable, soft, and unlikely to cause nutritional disorders. Lyrics of a song related to its use in livestock feeding are: *Mares eat oats, does eat oats, and little lambs eat ivy. A kid'll eat ivy, too, wouldn't you?*

Recently, oat has regained some popularity because of its cholesterol-lowering properties. Oatmeal is traditionally a breakfast food, but other cereal and food products containing oats such as granola are also marketed.

Oat is also used in cropping systems as a companion crop for establishment of small-seeded legumes such as alfalfa. In that system, oat can be harvested for hay or silage. Oat straw that is a by-product of grain production is valued for livestock bedding.

Rye

Rye (*Secale cereale*) grain coevolved as a weed with wheat or barley and became a crop in Europe by about 2000 BCE. Its use was associated with its greater cold and drought tolerance compared to other grains. Rye also tolerates soils with lower fertility better than other small grains. It was imported into North America and became an important bread crop and livestock feed in the colonies. As mentioned previously (see Chapter 15), consumption of rye grain has been associated with the Salem witch trials. A disease of rye grain, ergot, replaces the grain with a black

structure that contains hallucinogenic chemicals. Historical accounts indicate that many members of the Salem community were afflicted with symptoms of ergot poisoning, which were unfortunately associated with witchcraft and demonism. Many innocent people died because of this misdiagnosis.

Rye grain is used for bread, but because of its lack of gluten, rye alone cannot make raised bread. Rye is usually mixed with wheat gluten to produce raised bread. The grain can also be fed to livestock or fermented to produce rye whiskey. Its forage can be consumed by grazing livestock or made into hay.

Description and Adaptation

Rye grain is a tall-growing grass with multiple tillers. The inflorescence is a spike. It is grown as a winter or a summer annual. Winter rye is also used as a winter cover crop in northern latitudes to protect the soil from wind or water erosion. In corn production systems, winter rye has potential as a nutrient scavenger to pick up excess fertilizer nutrients remaining after corn harvest. In the spring, winter rye regrows rapidly and can be used for forage, or, if killed, as cover for corn and soybean production.

Sorghum

Sorghum (*Sorghum* spp.) is native to Africa, where the average air temperatures are hot and rainfall is limited. It was domesticated about 5000 BCE. It was first cultivated in the United States in the 1850s as a sugar and grain crop. Worldwide, sorghum ranks fourth after rice, corn, and wheat as a human food crop and is an especially important staple in drought-prone areas of the tropics. It is used mostly for livestock feed and forage in the United States in areas too hot or dry to support corn production. Kansas and Texas produce more than 80 percent of the sorghum in the United States, with smaller acreages in Nebraska, Colorado, South Dakota, and Oklahoma (Table 19-5). The United States is the number two producer and

TABLE 19-5

Acreage and yield of the top-producing states of grain sorghum in 2009. *Adapted from USDA-NASS (2010)*.

	Total area		Average yield	
State	in acres	in hectares	bu/acre	kg/hectare
Kansas	2,550,000	1,031,948	88	5524
Texas	2,050,000	829,606	48	3013
Oklahoma	220,000	89,031	56	3515
Colorado	150,000	60,703	45	2825
Nebraska	140,000	56,656	93	5837
South Dakota	120,000	48,562	61	3829
U.S. total	5,520,000	2,233,865	69	4331

the number one exporter of sorghum worldwide. Nigeria, India, Mexico, Sudan, and China are also leading producers of sorghum.

Description and Adaptation

Sorghum is a vigorous annual grass (Figure 19-18). It has a solid stalk up to an inch (2.5 cm) in diameter with many leaves that resemble those of corn. Most sorghums used for grain production in the United States have been selected for

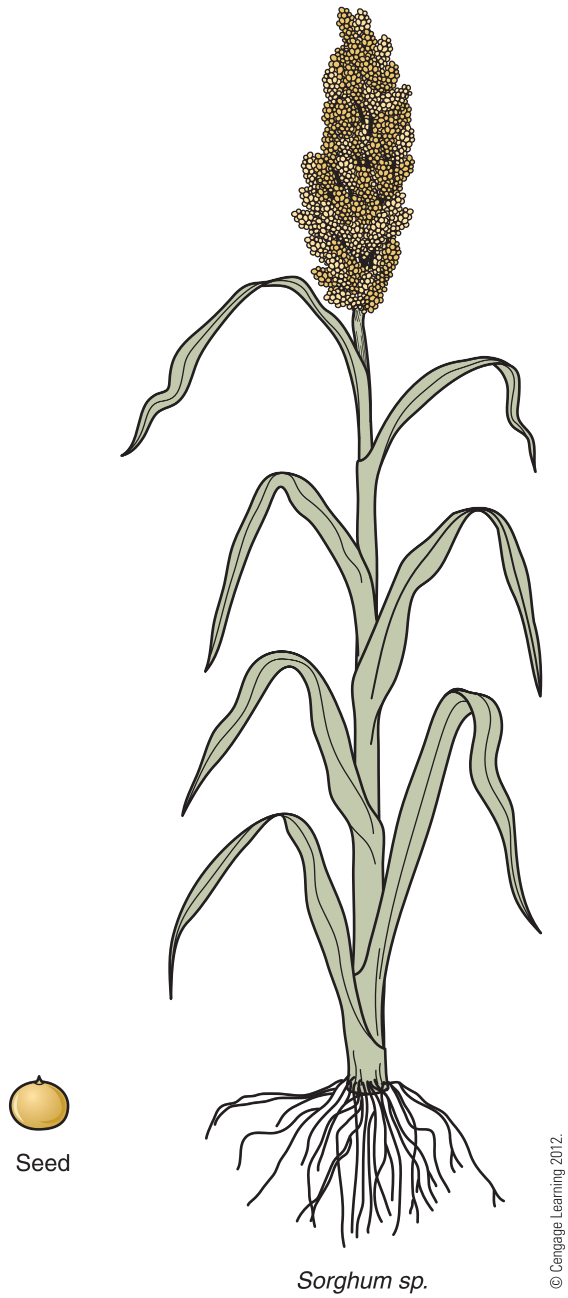


FIGURE 19-18
Sorghum is an important warm-season grain crop for low-rainfall regions.



FIGURE 19-19
Sorghum in the field.

short stature and are only 2–4 feet (0.6–1.2 meters) tall. Other types can be up to 15 feet (4.6 meters) tall. The sorghum inflorescence is a panicle that varies in shape depending on the type (Figure 19-19). A grain sorghum plant can have as many as 2000 oval grains. An extensive root system, waxy leaf surface, small leaf area, and ability to curl leaves are morphological features aiding sorghum's tolerance of dry conditions. In addition, during a growing season, sorghum can survive periods of moisture stress by becoming dormant and then resuming growth when conditions become favorable.

Sorghum is adapted to regions with high average temperatures (~85°F [29°C]) and rainfall of 10–25 inches (25–64 centimeters). It is intolerant of frost. There are four main types of sorghum based on use: (1) grain sorghums that are harvested for grain or whole plant for animal feed (Figure 19-20); (2) sweet sorghums that are used for silage and for syrup production; (3) Sudan grass, and Sudan grass hybrids that are used exclusively as a grazed or hay forage crop; and (4) broomcorn that is used for production of brooms. Grain sorghum grains can be boiled and eaten like rice, ground into flour for making unleavened bread or porridge, and brewed for beer. Starch in grain sorghum can be converted to ethanol like corn grains.

Sorghum syrup is a natural sweetener made by processing juice squeezed from the stalks of sweet sorghum. Sweet sorghum stalks contain up to 80 percent water that contains between 12 and 23 percent sugar. After concentrating the juice into syrup, yields of up to 300 gallons (1100 liters) of syrup per acre are



FIGURE 19-20
Sorghum stalks and some products produced from sorghum grain.

possible, though yields of 120 gallons (450 liters) per acre are typical. It takes about 8 gallons (30 liters) of juice to make 1 gallon (4 liters) of syrup. Sweet sorghum is being studied as an alternative for production of ethanol and can produce 400 to 800 gallons of ethanol per acre (3700 to 7500 liters per hectare). Sorghum juice, which contains mostly sugar, can be converted directly to ethanol.

Other Grains

Foxtail millet (*Setaria italica*), Japanese millet (*Echinochloa frumentaceae*), proso millet (*Panicum miliaceum*), finger millet (*Eleusine coracana*), and pearl millet (*Pennisetum glaucum*) are small-seeded annual members of the grass family. They are



FIGURE 19-21
Foxtail millet.

warm-season annual grasses that were domesticated in Africa up to 5000 years ago. They are very well adapted to excessive heat and drought, have deep roots, and tiller profusely. Foxtail and proso millet produce seed 60–90 days after planting. Millets are the sixth most important grains in the world for human consumption with India and Africa leading global production. Pearl millet is the most important and widely grown of all of the millets. They are used for human food and livestock feed and are an important staple crop in semiarid areas of India, Africa, and China. Their small seed size makes modern harvesting and processing challenging; however, the vast majority of millets are consumed locally and are not exported. Grain heads are often harvested by hand and, because of their excellent storage capacity, are stored in elevated granaries for use as needed. Grains are often boiled like rice, ground for flour to make unleavened bread or porridge, roasted whole, and used for beer making. Millet grain is best known in the United States for domestic bird (e.g., parakeet) food and wild bird food (Figure 19-21). It can also be fed to poultry and other livestock. Like other grains, it is high in energy and is deficient in some amino acids. Pearl and foxtail millet can also be harvested as forage.

Nongrass Grains (Pseudocereals)

Pseudocereals are used similarly to grain crops like wheat and rice, but they do not belong to the grass family. Pseudocereals have been cultivated in all parts of the world. **Quinoa** (*Chenopodium quinoa*), **amaranth** (*Amaranthus cruentus* and other *Amaranthus* spp.), and buckwheat are some important pseudocereals for human consumption, both historically and currently. All of these crops are broad-leaved annuals that produce edible grain-like seeds, which are high in protein and amino acid content.

Quinoa, known as the "mother grain" to the Inca people, was a vital food crop native to the South American Andes Mountains. It was domesticated by native peoples 3000–5000 years ago. It is closely related to lambsquarters, a common

annual agricultural weed. The plants grow 3–7 feet (0.9–2.1 meters) tall and produce an abundant amount of small, circular, flat seeds. Both the seeds and the leaves are edible. Today, the grain is growing in popularity in health-food stores and co-ops due to its exceptionally high protein and balanced set of amino acids; it is often prepared by washing and boiling like rice, or ground as a flour additive. The majority of world production still comes from Peru, Bolivia, and Ecuador where it is grown at high altitudes of 13,000 feet (4000 meters) or more. Quinoa is adapted to specific environmental conditions. It grows best on well-drained soils, at temperatures of 45–50°F (7–10°C), and at short daylengths. Temperatures above the optimum range will hinder rate of development and abort flowering.

Amaranth is an alternative grain crop that produces a highly nutritious grain (Figure 19-22). It is related to the pigweeds (*Amaranthus* spp.) that are important broadleaf weeds in grain and forage crops. Amaranth is a high protein grain that is ground for flour, toasted, or popped and sold as a specialty "health food" product. The edible leaves can be consumed as a vegetable. Historically, it was an important staple crop to the Aztec Indians of Central America, but cultivation was



Craig Sheaffer.

FIGURE 19-22
Amaranth plant.

TABLE 19-6

Nutritional composition of pseudocereals based on a 100-gram sample. *USDA National Nutrient Database for Standard Reference (2010).*

Pseudocereal	% water	Calories	Protein, g	Fat, g	Carbohydrate, g	Fiber, g
Quinoa	13.3	368	14.1	6.1	64.2	7.0
Amaranth	11.3	371	13.6	7.0	65.3	6.7
Buckwheat	9.8	343	13.3	3.4	71.5	10.0

actively suppressed following the Spanish invasion of the Americas. Along with corn and beans, it was a foundational crop to the success of the Aztec empire and was involved in many rituals and religious ceremonies. Amaranth can grow up to 8 feet (2.4 meters) tall and is prized not only for its edible seeds and leaves, but also its ornamental value in gardens. Amaranth is a warm-season species that is grown as a summer annual. It is adapted to heat and drought. Amaranth seed is very small with over 500,000 per pound, so planting and harvesting can be challenging. Amaranth has been evaluated in Minnesota for use as an annual forage crop. Herbage yields at 16 weeks after planting were 4 tons per acre (9 tonnes per hectare) with a forage-protein concentration of 15 percent.

Buckwheat (see Wheat section for description) is also considered a pseudocereal. The nutritional content of the pseudocereals is shown in Table 19-6.

Forage Grasses

Forage grasses provide multiple, important functions to our society. In addition to providing feed for livestock, they sustain the environment by providing soil and water conservation, and they provide wildlife habitat and recreational opportunities. The combined U.S. acreage of perennial and annual forage grasses exceeds that of cultivated, annual commodity crops like corn, soybean, or small grains (see Chapter 2). Forage grasses are an important source of nutrients for many types of livestock, especially ruminants such as cattle and sheep. Forage grasses are harvested directly by grazing or mechanically as hay or silage. A diversity of perennial and annual grasses is used for forage. Species used in specific regions of the United States are influenced by the climatic and soil conditions. We present the numerous forage grasses as two broad groupings: cool and warm season.

Cool-Season Perennial Grasses

There are many cool-season forage grasses. These grasses are grown alone or mixed with legumes such as alfalfa and red clover. **Cool-season grasses** can be grouped into two general categories: tall-growing and short-growing cool-season grasses.

Tall-growing, cool-season grasses. These include smooth bromegrass, meadow fescue, reed canary grass, orchard grass, perennial ryegrass, timothy



FIGURE 19-23
Timothy is a tall-growing, cool-season forage grass. It is preferred for horse hay.

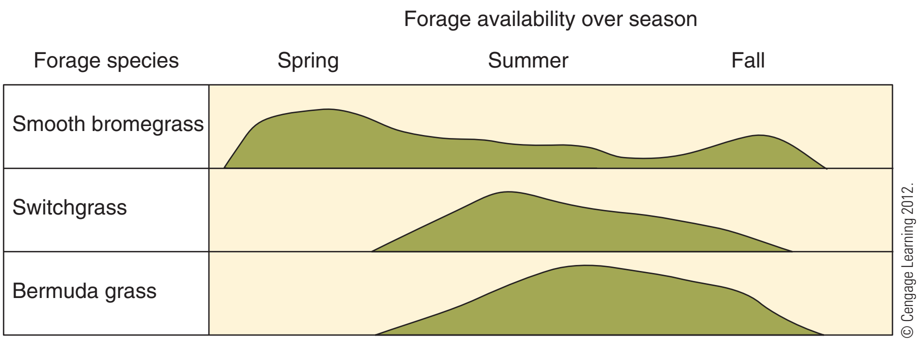


FIGURE 19-24
Forage availability by season. Smooth brome is a cool-season forage, while Bermuda grass and switchgrass are warm-season forages.

(Figure 19-23), and tall fescue. Cool-season grasses grow best in cool, moist climates with optimum growth temperatures about 75°F (24°C). Their growth is reduced at temperatures above 90°F (32°C) and by drought. Wheatgrasses and wild rye also grow best at temperatures below 90°F (32°C), but in addition have significant drought tolerance. Perennial cool-season grasses, except for perennial ryegrass and tall fescue, are usually very winter hardy. In northern regions, perennial cool-season grasses grow from spring to fall, but the pattern of growth varies among species (Figure 19-24). In southern regions with less severe winters, they may also be used in fall and winter.

Tall-growing grasses typically reach a height of 3–4 feet (0.9–1.2 meters) at flowering stages, and have a high yield potential of 3–7 tons/acre (7–14 tonnes/hectare).

TABLE 19-7

Effect of nitrogen rate on cool-season grass yields. *Adapted from Casler et al. (2008).*

	Nitrogen rate (pounds/acre)					Nitrogen rate (kilograms/hectare)				
	0	60	120	180	240	0	67	135	202	269
Species	---- Tons dry matter per acre ----					---- Tonnes dry matter per hectare ----				
Tall fescue	0.87	1.23	1.81	2.30	2.61	1.95	2.76	4.06	5.16	5.85
Orchard grass	0.79	1.37	1.91	2.22	2.58	1.77	3.07	4.28	4.98	5.78
Meadow fescue	0.75	1.25	1.69	2.00	2.41	1.68	2.80	3.79	4.48	5.40

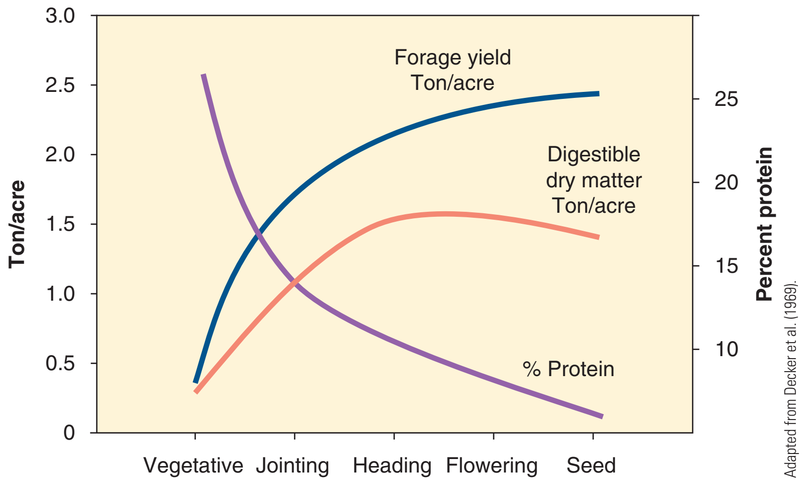


FIGURE 19-25
Effect of cool-season grass maturity on yield and quality.

Yield is greatly influenced by nitrogen fertility that can be supplied either by synthetic fertilizers, manure, or legumes grown in mixture (Table 19-7). These grasses all flower in the spring and, if harvested, the regrowth will be vegetative without flowers (Figure 19-25). They are typically harvested 3–6 times per growing season which results in greater yields, but lower forage nutritive value when compared to less frequent harvesting.

There are also native and introduced tall-growing, cool-season grasses—wheatgrass (e.g., western wheatgrass, slender wheatgrass, crested wheatgrass) and wild rye (e.g., Canada wild rye, blue wild rye, Russian wild rye)—that are adapted to semiarid and arid environments in the western United States. This region typically averages from 10–20 inches (25–50 centimeters) of rainfall annually and forage yields average from 1–4 tons/acre (2–9 tonnes/hectare). See Table 19-8 for forage yields for native cool-season grasses.

Short-growing, cool-season perennials adapted to humid regions. Kentucky bluegrass is the most widely used short-growing cool-season species. Red top is another short-growing species that volunteers in some northern pastures, but it is not often deliberately seeded. Kentucky bluegrass is most commonly found in permanent pastures and is used mostly for grazing. It is also used extensively as a turfgrass (Figure 19-26). Kentucky bluegrass has a shallow root system and is more susceptible to heat and moisture stress than tall grasses. It forms

TABLE 19-8

Mean forage yields for several cool-season grasses in Hettinger, ND, 1995–1997. *Adapted from Sedivec et al. (2008a).*

Grass	Variety	Yield lb/acre	Yield kg/hectare
Tall wheatgrass	Alkar	4583	5137
Altai wild rye	Prairieland	4000	4483
Crested wheatgrass	Nordan	3863	4330
Intermediate wheatgrass	Reliant	3928	4403
Smooth bromegrass	Cottonwood	2592	2905
Russian wild rye	Bozoisky Select	2379	2667



FIGURE 19-26
Kentucky bluegrass is a short-growing, cool-season forage and turfgrass.



Tall Fescue and the Fungus

Tall fescue (*Schedonorus phoenix*, formerly *Lolium arundinaceum*) is a perennial forage grass that is native to Europe. It was introduced into the colonies in the 1700s, likely as contaminant with other grass seeds. It became widely grown in the southeastern region of the United States in the mid-1900s with the release of the first, improved tall fescue of 'Kentucky 11' by Dr. E. N. Fergus, a professor at the University of Kentucky, who selected it from an overgrazed pasture on a Kentucky hillside. Tall fescue is adapted to a wide variety of environmental conditions and is more tolerant of heat, drought, infertile soils, and overgrazing than other cool-season grasses. Tall fescue is especially valued in mild winter areas because of its significant growth in late winter and in the fall. It is planted on over 30 million acres in the southeastern and south-central United States. It is adapted to the transitional climate zone between the climate ideal for the cool-season species in the north and warm-season species like Bermuda grass in the south. It has less winter hardiness than other cool-season grasses and sometimes winter-kills in northern states like Minnesota and New York. Tall fescue is harvested for hay and silage, but is most widely used for pasturing of beef cows, dairy cows, and calves.

Despite its widespread use and importance to the livestock industry, beef animals grazing tall fescue sometime refuse to eat it and have poor performance. They develop health problems that collectively are known as *tall fescue toxicosis*. These include fescue foot (where cattle lose their hooves and tails), fat necrosis (where large fat deposits accumulate along the digestive tract), and summer syndrome (where animals have poor heat tolerance and fail to shed their winter hair coats). After years of investigation, researchers in Kentucky, Georgia, and Alabama found that tall fescue toxicosis is associated with the presence of a fungus in the seed and herbage that produces alkaloids. That fungus is called an *endophyte* because it lives within the plant. Dr. Carl Hoveland at the University of Alabama was a leader in studying tall fescue toxicosis and released one of the first fungi-free cultivars, 'AU-Triumph'. Scientists soon found that the new fungi-free varieties were readily eaten but failed to persist. Further study showed that tall fescue and the fungi had a beneficial "mutualism" where both the plant and the fungi benefited from the association. The plant supplied energy and housing to the fungi while the fungi protected the plant from herbivory, diseases, and drought. Now new varieties of tall fescue have been developed containing a fungus that does not produce toxic alkaloids. These new varieties are persistent and give good animal performance; they are being used by producers to replace endophyte-infected varieties such as 'Kentucky 11'.

sod through the growth of rhizomes. Kentucky bluegrass grows from 6–12 inches (15–31 centimeters) tall and has narrow leaves. Yield potential is from 2–3 tons/acre (5–7 tonnes/hectare).

Origin

Most of the widely used, cool-season forage grasses originated in temperate, northern regions of northern Europe and northeastern Asia. Historically, perennial grasses were the dominant forages used by native and domesticated animals. They predominated in the great grass biomes in the world and were among the first forages to be used once animals were domesticated. Most of the commonly used grasses adapted to humid regions were purposely or accidentally introduced into North America during colonial times. Some species such as *Calamagrostis*, *Poa*, and *Phalaris* are native to North America. For example, wheatgrasses and wild ryes are native to the northern Great Plains of the United States, but some types were also introduced.

Warm-Season Perennial Grasses

Warm-season grasses make optimum growth at temperatures around 90°F (32°C). They have little growth below 50°F (10°C). Therefore, in temperate regions, warm-season grasses have a pronounced winter dormancy. Most native, warm-season grasses also have greater tolerance to moisture deficits than cool-season grasses. Native warm-season species will survive extreme winter cold while introduced warm-season species such as Bermuda grass will not.

Warm-season grasses have many of the same morphological features as cool-season grasses, but all have distinguishing characteristics. Big bluestem, switchgrass, and Indian grass typically grow 5 feet (1.5 meters) tall, but can reach a height of 10 feet (3 meters). They have robust root systems capable of reaching a depth of 10 feet (3 meters). Switchgrass and big bluestem have rhizomes and can form a very dense sod.

These grasses are used for summer grazing and for haymaking. Native species are also used for prairie restoration efforts. Their extensive root systems are effective at soil stabilization, and these plants are sometimes used at erosion control sites. Switchgrass and mixtures of other warm-season native perennials have been proposed as cellulosic energy crops (see Chapter 4).

Two categories of warm-season grasses—native and introduced—are used in the United States and Canada.

Native warm-season perennial grasses. These grasses are best adapted to prairie and dryland regions. These include big bluestem (Figure 19-27), switchgrass, Indian grass, little bluestem, and buffalo grass (Figure 19-28). Warm-season perennial grasses are native to North America and made up the tallgrass prairies. The tallgrass prairies were mostly destroyed during settlement, although remnants remain. Little bluestem and buffalo grass were among the shorter stature grasses that are prevalent in more arid regions. In addition, many other species such as needlegrass and grama grass were specifically adapted to unique environments. See Table 19-9 for forage yields for native cool-season grasses.



FIGURE 19-27
Big bluestem is also known as turkey foot grass because of its distinctive inflorescence.



FIGURE 19-28
Buffalo grass is a short (2–7 inches [5–18 centimeters]), native, perennial grass that is spread by aboveground stems or stolons. Buffalo grass is dioecious and has both male and female plants. Buffalo grass is native to the central and southern Great Plains and is tolerant to drought and excessive grazing.

TABLE 19-9

Mean forage yields for several warm-season grasses in Hettinger, ND, and Fort Pierre, SD, 1999–2000. *Adapted from Sedivec et al. (2008b).*

Grass	Variety	Yield	
		lb/acre	kg/hectare
Switchgrass	Forestburg	4594	5149
Big bluestem	Sunnyview	3180	3564
Little bluestem	Camper	2236	2506
Indian grass	Holt	2082	2334
Sideoats grama	Butte	1516	1699

Introduced Perennial, Subtropical, Warm-Season Grasses

Grasses such as Bermuda grass, bahia grass, and Dallis grass are used as perennial warm-season forages in the southern United States. They are used for pasture and hay production. Other grasses grown in the humid South include limpograss, elephant grass, and digitgrass.

Bahia grass and Dallis grass were introduced from South America and are adapted to the climate and soils from southern Florida to eastern Texas. Bahia grass is a rhizomatous, sod-forming species that grows better on low fertility, droughty soils than Bermuda grass. It is used mostly as a pasture grass and is more tolerant to close and frequent grazing than Bermuda grass. Dallis grass is a bunch grass that is noted for its adaptability to climates with high, annual rainfall and to poorly drained soils. It is mostly used as a pasture grass.



Switchgrass: A Native Biofuel Crop

Switchgrass (*Panicum virgatum*) was one of the original native grasses that, along with big bluestem, predominated the tallgrass prairie that covered the Great Plains prior to European settlement. It is adapted to most of North America from the Rocky Mountains to the Atlantic Coast (Figure 19-29). Switchgrass has a coarse, wide-leafed forage and can grow up to 10 feet tall (3 meters). Switchgrass is a C_4 warm-season grass and makes most of its growth in late June, July, and August. Switchgrass is adapted to a wide range of soils and better adapted to sites without moisture stress. Switchgrass has been traditionally used for hay and pasture. It also can provide wildlife habitat. Forage yields with current varieties average 2–3 tons/acre (4.5–6.7 tonnes/hectare) in the northern sites to as high as 12 tons/acre (27 tonnes/hectare) at southern sites. There are upland- and lowland-variety types that vary in yield potential, and

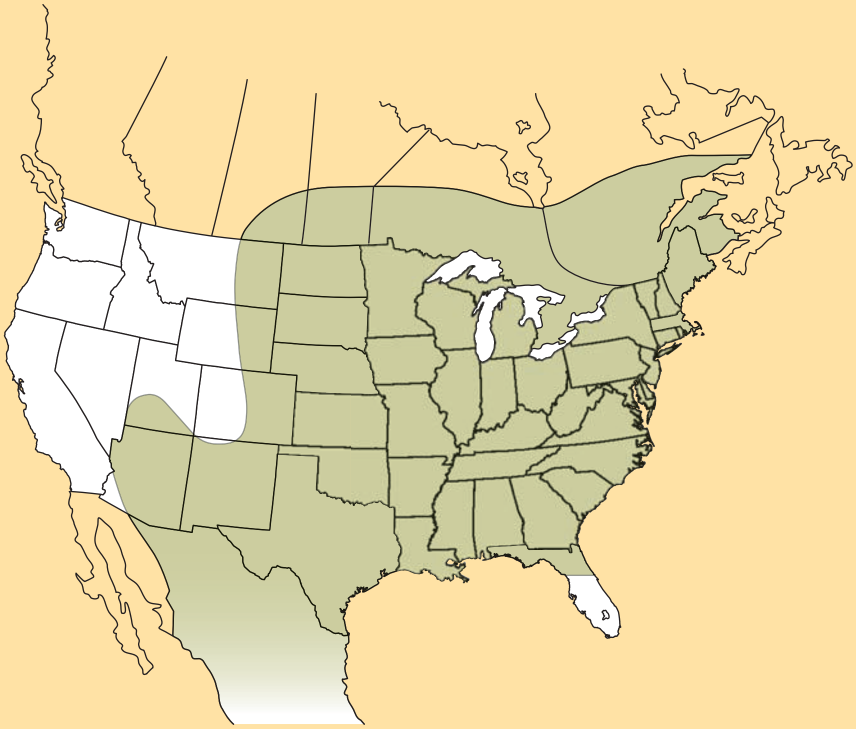


FIGURE 19-29 Area of adaptation for switchgrass.

breeding is underway to select for new, lowland types of switchgrass with greater yield potential (Figure 19-30).

Recent research conducted by scientists at the University of Nebraska and with the USDA-ARS has confirmed the viability of using switchgrass as a renewable biofuel crop. At 10 farm sites in Nebraska, North and South Dakota over a 5-year period, Schmer et al. (2008) found switchgrass produced biomass yields ranging from 2–5 tons/acre (5–11 tonnes/hectare) that on average were equivalent to 320 gallons of ethanol per acre (3000 liters per hectare). Switchgrass produced 540 percent more renewable than nonrenewable energy consumed in its production and harvesting. Moreover, they found that switchgrass could add a significant amount of carbon to the soil. Liebig et al. (2008) reported that with production of switchgrass, soil organic carbon increased significantly at 0–12 inches (0–30 cm) and 0–47 inches (0–120 cm) with accrual rates of 0.5 to 1.3 tons C/acre per year (1.1 and 2.9 tonnes C/hectare per year).

(*Continued*)



Stephen Ausmus, USDA-ARS.

FIGURE 19-30 Elite-type switchgrass being researched for biofuel in Nebraska.

Bermuda Grass: An African Native

Bermuda grass (*Cynodon dactylon*) is the leading warm-season grass in the southern United States. It is used for hay and grazing as well as for turfgrass. It is productive from Virginia to New Mexico, although irrigation is needed for good productivity in the West (Figure 19-31). Bermuda grass is a native of southern Africa and was brought to the Georgia colony for use as a pasture grass in the mid-1700s. Bermuda grass grows best at temperatures above 75°F (24°C); temperatures below 30°F (–1°C) kill the herbage to the soil surface. Bermuda grass is very drought-tolerant and tolerates low fertility soils. Wild types of Bermuda grass are propagated by seed, rhizomes, and stolons; it can be a weed in row-crop production.

Dr. Glenn W. Burton (1910–2005), a plant breeder with the USDA-ARS at Tifton, Georgia, was a pioneer in improving Bermuda grass for the South. In 1943, after many years of experimenting, he developed the first, improved Bermuda grass variety, 'Coastal' Bermuda grass, which is still among the most widely grown Bermuda grass varieties. It has over twice the yield potential as unimproved Bermuda grass and greater drought tolerance. It has high yield and responds to nitrogen fertilization (Table 19-10). 'Coastal' Bermuda grass has sterile seed and is propagated by incorporating harvested stolons. During his 60-year career, Dr. Burton released six more improved varieties, including 'Tifton 85', and identified harvest management and soil fertilization practices to maximize the production of high-quality forage. It is estimated that improved Bermuda grasses are grown on over 10 million acres (4 million hectares) in the South today.

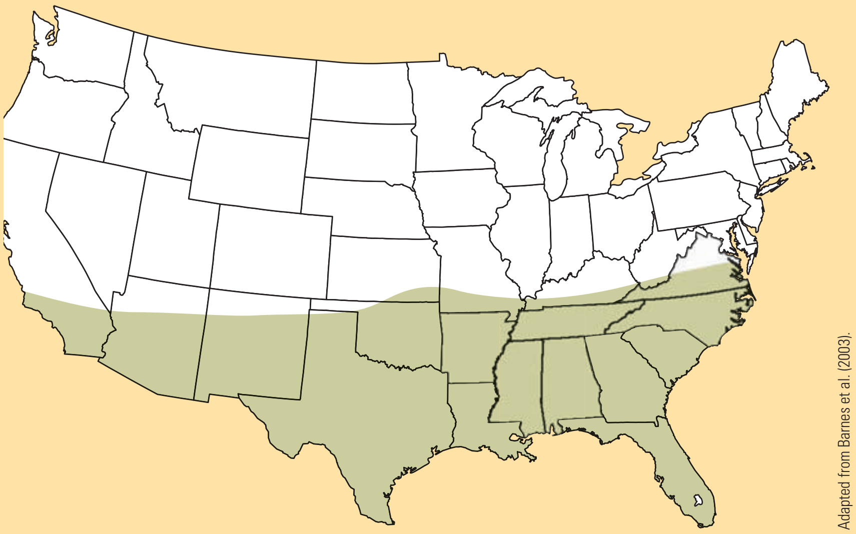


FIGURE 19-31 Area of adaptation for Bermuda grass.

TABLE 19-10

The effect of nitrogen rate on hay production of 'Coastal' Bermuda grass. *Adapted from Prine and Burton (1956).*

	Yield	
Nitrogen rate	tons/ac	tonnes/ha
0	1.6	3.7
100	4.6	10.2
300	7.8	17.5
600	10.2	22.9
900	11.0	24.7

Review Questions

1. What are the three crops grown on the largest acreage in the world today? What crops are grown on the largest acreage in the United States?
2. Explain the uses of corn in the United States.
3. Name and describe the six primary types of corn.
4. What are the market classes of wheat that are grown in the United States and what are they used for?
5. What is triticale?
6. What are the two main types of rice?
7. What is the only native North American grain crop? Examine its history.
8. Describe how beer is made.
9. Describe the different small grains (barley, oats, and rye) and give uses for each.
10. What is sorghum and what can it be used for?
11. Describe the differences between cool- and warm-season grasses and give examples of each.
12. Discuss the history and use of tall fescue, Bermuda grass, and switchgrass.

Critical Thinking

1. Review the origin and history of corn. What features of the corn plant made it desirable to Native Americans? What are some of the desirable traits for which Native Americans selected?
2. Go to a local supermarket and examine the ingredient lists of a diversity of products. For the products you examined, identify which ones contained cereal grains.
3. Determine the primary forage grasses that are grown in your state and indicate how they are used.
4. Breadmaking has been an important part of all cultures. Review the history of breadmaking in the world and identify what crops were used.
5. Review earlier chapters and clarify the physical and nutritional differences between whole grain bread and white breads.

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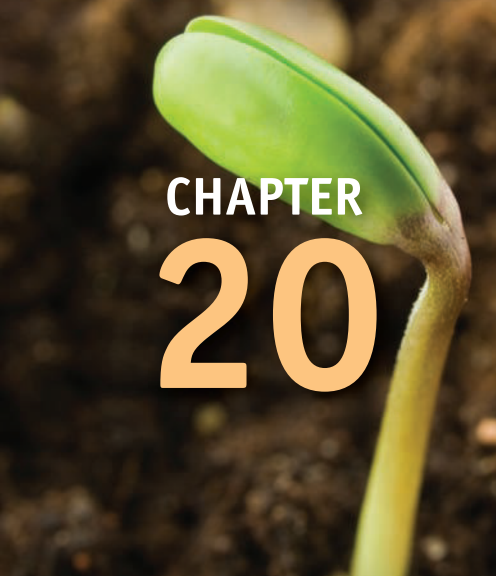
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CHAPTER 20

Crop Profiles: Legumes





Key Concepts

- Plants in the legume family have compound leaves, bear seed in pods, and can conduct biological nitrogen fixation.
- Legumes are harvested for grain or forage.
- Soybean is the most important grain legume.
- Soybeans are used for direct human consumption and for crushing for oil and meal production.
- Field beans include kidney beans, navy beans, pinto beans, black beans, cranberry beans, and great northern beans. They are consumed mostly by humans.
- Peanuts are used in snack foods, peanut butter, and candy. They can be pressed to extract oil.
- Lentil, lupine, and chickpea are other grain legumes.
- Forage legumes are used as a source of high-protein livestock feed.
- Alfalfa is the most widely grown forage legume.
- Other forage legumes include annual and perennial clovers, birdsfoot trefoil, sweet clover, vetches, and sainfoin.

Key Terms

alfalfa
berseem clover
birdsfoot trefoil
bloat
chickpea
clover
cowpea
crimson clover
faba bean
field bean
field peas
kura clover
lentil
lupine
maturity group
peanut
peg
red clover
sainfoin
soybean
sweet clover
vetch
white clover

Introduction

The legume (or bean) family (Fabaceae or Leguminoseae) includes a number of important crop species including pulse crops such as soybean, peas, and beans, as well as forage legumes such as alfalfa and the clovers. Most legumes conduct biological nitrogen fixation in symbiosis with rhizobia. Their foliage and seeds are rich in protein (Table 20-1). They also all have compound leaves and bear their seed in pods. In Chapter 21, we discuss several grain and forage legumes.

Soybean

Soybean (*Glycine max*; soya) is native to China. It is one of the oldest cultivated crops and is likely related to *Glycine ussuriensis*, a small-seeded, wild relative still found in the region. The Chinese domesticated it nearly 3000 years ago, and it was regarded as a sacred grain essential for survival of their culture. It was imported into Japan and Korea early in the first century and into Europe in the early 1700s. Soybeans came to North America in the early 1800s and were first used as an annual hay crop and for plow down as a green manure. George Washington Carver experimented with soybean as a food source in the early 1900s. An early promoter of the soybean was Henry Ford, founder of Ford Motor Company. He processed soybean and extracted the oil for use in paint and plastic manufacture. Large-scale commercial production of soybean in the midwestern United States began in the 1920s.

Soybean is the most important grain legume crop in the world and among the top five of all food crops grown. The United States is the largest soybean producer. In 2005, the soybean crop was grown on 74 million acres (30 million hectares) and was valued at $19 billion. It is often grown in rotation with corn. The leading soybean states are Iowa, Illinois, Minnesota, Indiana, and Nebraska.

TABLE 20-1

Nutritional composition of food legumes based on a 100-gram sample. *USDA–National Nutrient Database for Standard Reference (2010).*

Legume (all raw)	% water	Calories	Protein, g	Fat, g	Carbohydrate, g	Fiber, g
Pinto beans	11.3	347	21.4	1.2	62.6	15.5
White beans	11.3	333	23.4	0.9	60.3	15.2
Black beans	11	341	21.6	1.4	62.4	15.2
Kidney beans	11.8	337	22.5	1.1	61.3	15.2
Chickpeas	11.5	364	19.3	6.0	60.1	17.4
Lentils	10.4	353	25.8	1.1	60.1	30.5
Peanuts	6.5	567	25.8	49.2	16.1	8.5
Peas	11.3	341	24.6	1.2	60.4	25.5
Soybeans	8.5	416	36.5	19.9	30.2	9.3

Description and Adaptation

Soybean is an annual crop that produces seed in pods on upright stems that are from 3–4 feet (0.9–1.2 meters) tall (Figure 20-1). Stems can be single or have multiple branching that is influenced by variety and environmental conditions. Pinnately compound trifoliolate leaves are alternately attached to the stem that terminates in a meristem. The stems, leaves, and pods are covered with a fine brown or gray pubescence. Small legume flowers that are varying shades of purple to white are borne in the leaf axils beginning at the bottom of the plant. Mature pods contain from three to five seeds. Soybean seeds are spherical and vary in color from yellow to black (Figure 20-2). Hilum (the point on the seed that once was connected to the pod) color varies from yellow to black.

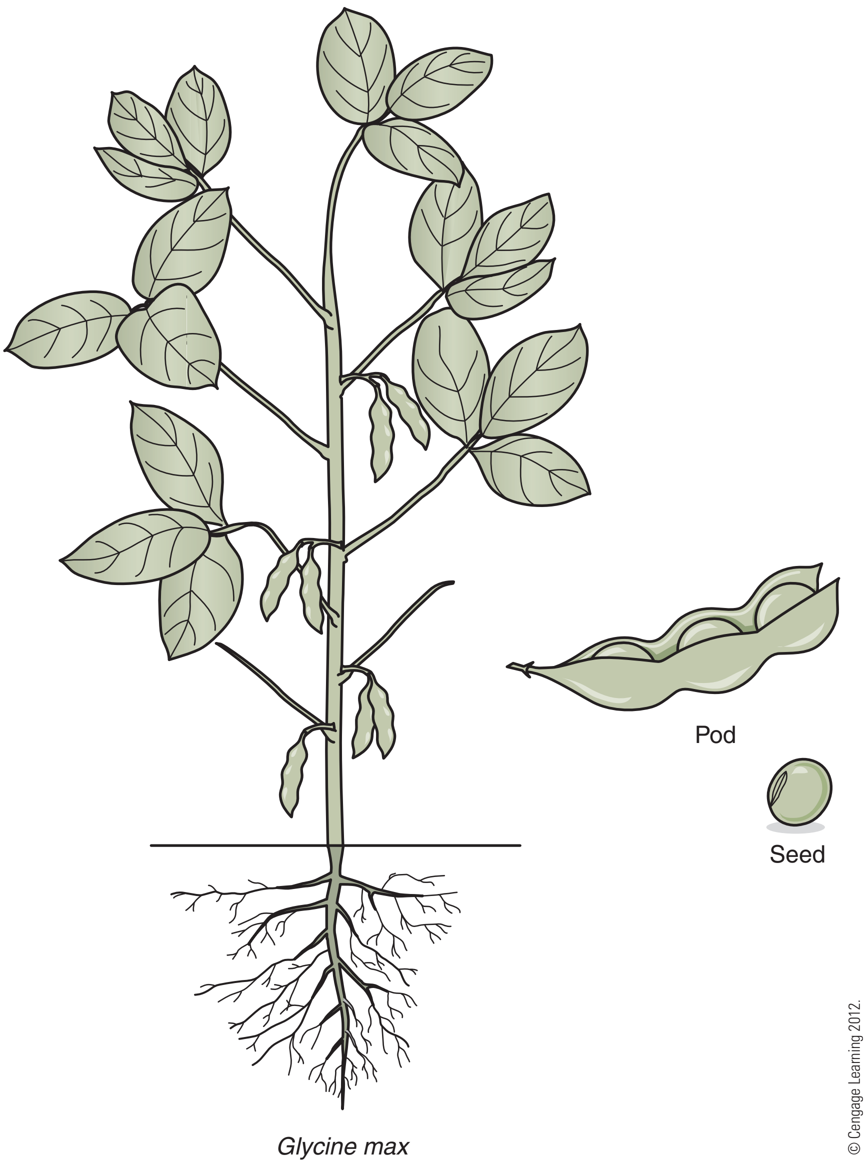


FIGURE 20-1
Soybean is the most widely grown legume grain crop.

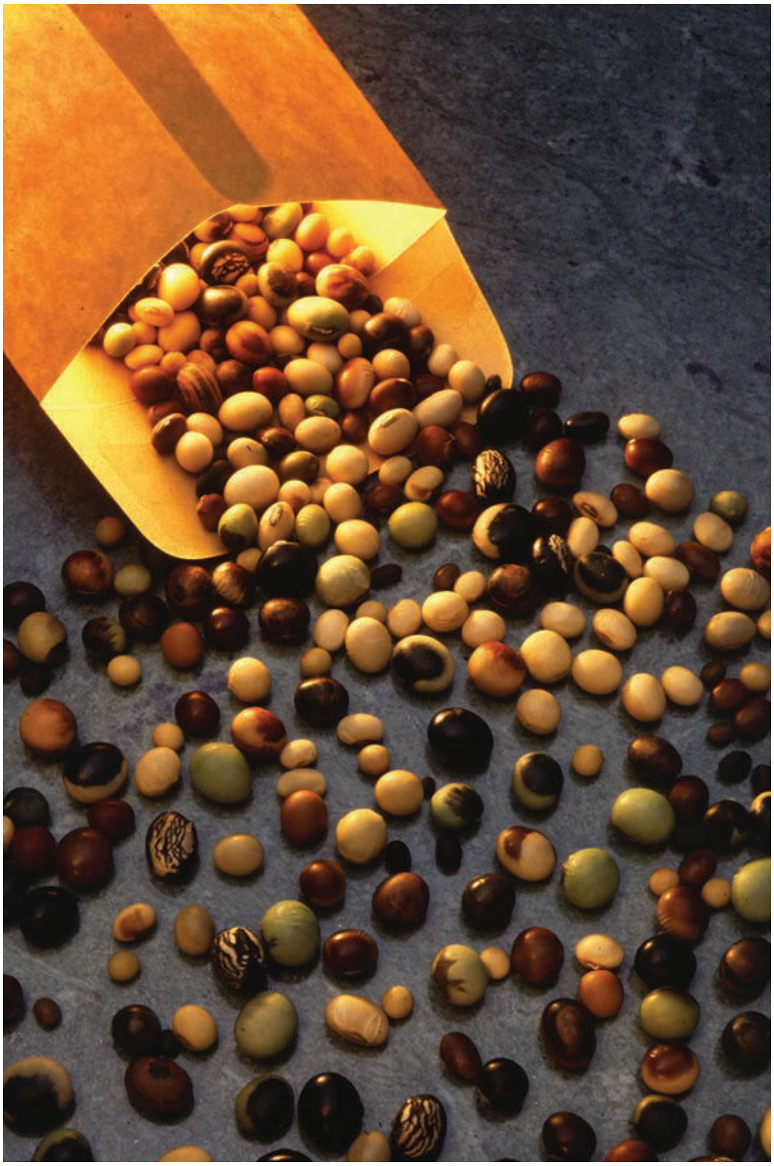

Scott Bauer, USDA-ARS.

FIGURE 20-2
Some of the many types of soybean.

Soybean varieties grown in the northern United States and Canada are determinant, and those grown in southern regions are indeterminant in growth habit. Indeterminant varieties are those that have continual stem elongation throughout the growing season because the terminal (or apical) meristem remains vegetative. Conversely, determinant varieties cease stem elongation when the terminal meristem converts from vegetative to floral. Soybean is taprooted with a large number of secondary roots. Most roots are in the top 12 inches (31 centimeters) of soil, but some can extend over 6 feet (1.8 meters) into the soil. Spherical nodules formed by *Rhizobium* are the site of symbiotic nitrogen fixation. Through this process, soybeans are able to meet their nitrogen needs for growth and do not require nitrogen fertilizer.

There are two categories of soybean varieties: those intended for direct human consumption and those intended for processing or crushing. Soybean varieties with yellow or brown seeds and yellow hilum are commonly crushed for oil and soy-flour production. The seed contains about 35 to 40 percent protein, 35 percent carbohydrates, 20 percent oil, and 5 percent ash. The oil contains linolenic, linoleic, and oleic fatty acids. The protein is complete and contains all the essential amino acids. In diets, it provides the amino acids lysine and tryptophan that are deficient in foods from the grass family such as corn and wheat. The carbohydrates in the seed are mostly sucrose and sachyrose (a compound of sucrose and galactose). Seed also contains the insoluble carbohydrates cellulose, hemicellulose, and pectin that have value as dietary fiber.

Soybean is a warm-season crop and is adapted to climates and soils where corn is grown. Soybeans are grown as summer annuals. Soybeans flower in response to short days. Soybean varieties are classified into 13 **maturity groups** (000 to X) that are adapted to specific latitudes and growing seasons. Groups 00 to IX are soybeans most adapted to the United States (Figure 20-3). Group 00 soybean varieties are the earliest maturity varieties that flower and mature under the long days of northern latitudes, whereas group IX soybeans are adapted to the longer growing seasons in the south of the United States.

Use

About 85 percent of the world's soybeans are processed into meal and oil with the remainder used directly as human food. Soybean oil is chemically extracted following crushing the seed. Most of the meal is used as a protein ingredient for

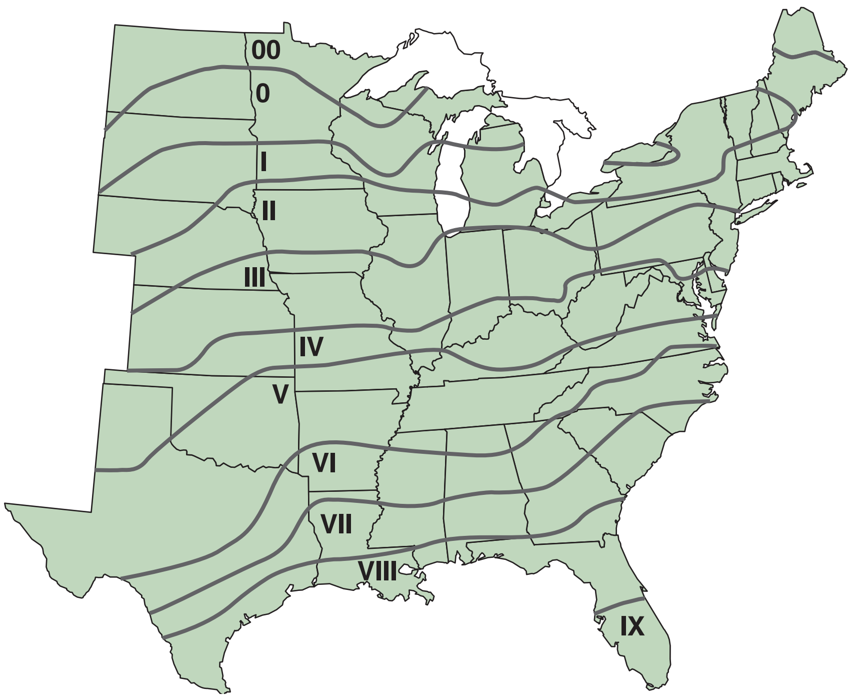


FIGURE 20-3
Soybean maturity group zones for the United States.

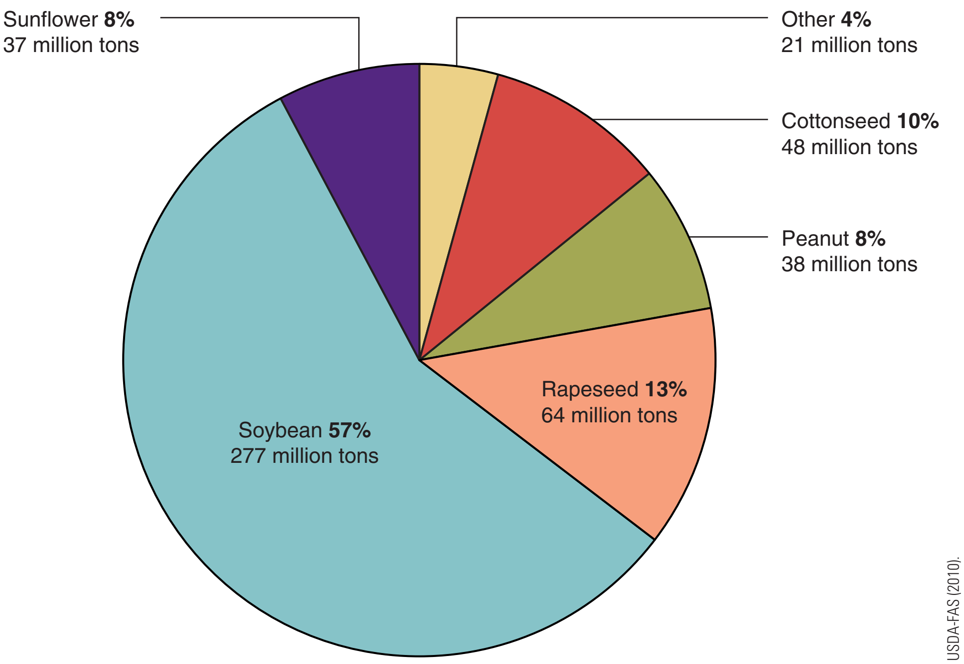


FIGURE 20-4
World oilseed production in 2010.

livestock feed. Most of the oil is consumed by humans and the rest is used for industrial products. Raw soybeans contain trypsin inhibitors (protease inhibitors) that reduce protein digestion by humans, swine, and chickens; therefore, soybeans are cooked or roasted before use.

Soybean is the most important oilseed crop in the world (Figure 20-4). Soybean oil is mostly polyunsaturated and monounsaturated (see Chapter 6). It is the most widely used cooking oil in the United States and is used for frying and as a component of margarine and salad dressing. It is hydrogenated for use in margarines. The oil is used industrially for production of inks, paints, cosmetics, caulk, linoleum, and biodiesel. See Chapter 5 for more information on biodiesel.

Some important soybean foods or food ingredients include the following:

- Soy flour. It is made by grinding roasted soybeans. It contains 50 percent protein. Soy flour can be made into textured soy flour by extruding moistened soy flour into different shapes and sizes.
- Soy protein products. These are made by mixing soybean protein with other ingredients and forming them to make a product appealing to consumers. These products are sold as frozen, canned, or dried foods.
- Lecithin. This is a phospholipid compound extracted from soybean oil. It is used in the food industry as an emulsifier to provide uniform mixing of components, especially of fats. It is also used as a lubricant.
- Beverages and infant formulas. These can be made with soymilk or isolated soy protein. Soymilk is produced by soaking, grinding, and straining soybeans. For flavor, fruit juices or other ingredients are added.



Soybean Growers Association

The Soybean Growers Association was founded in 1920 and organized soybean growers throughout the Midwest and United States. Prior to this time, soybeans were a relatively minor crop. The Soybean Growers Association advocated for guaranteed minimum pricing for soybeans, which helped to increase production throughout the 1930s. The early association also advocated for increased use of soybean meal for animal feed, larger utilization of the edible oil and fats from soybean oil, and exporting the crop to European and Asian markets.

Today, the organization has over 25,000 members and is a voluntary, dues-based membership organization. Through lobbying and advocacy, the Soybean Growers Association works toward increasing the use of soybean products and by-products by consumers, industry, and government. Like the Corn Growers Association, the Soybean Growers Association works with affiliated state offices and utilizes state checkoff funds. Some of the most notable achievements by the organization include: promoting the use and production of soy-based biodiesel, working to include soybeans in price-support and agricultural-subsidy structures, marketing campaigns to decrease the use of tropical oils in favor of soy oils, and opening new markets for American soybeans through the Central America Free Trade Agreement (CAFTA) and other trade agreements. For more information on the Soybean Growers Association, see their website at <http://www.soygrowers.com/>.

- Edamame. These are large, vegetable soybeans harvested when the beans are still green and sweet tasting. They are high in protein and fiber and contain no cholesterol.
- Natto and miso. These are made by fermenting soybeans. They vary in flavor and are used in a variety of ways such as a topping for rice and vegetables. Miso is used as an ingredient in soups.
- Soynuts. These are whole soybeans that have been soaked in water and then roasted until browned. Soynuts are similar in texture and flavor to peanuts.
- Soy sauce. This is a dark-brown liquid made from soybeans that has undergone a fermenting process. Soy sauces have a salty taste, but are lower in sodium than table salt.
- Tofu. This is a soft, cheese-like food made by curdling fresh, hot soymilk. Tofu is a bland product that easily absorbs the flavors of other ingredients with which it is cooked. Tofu is rich in both high-quality protein and B vitamins and is low in sodium. Silken tofu is a creamy product and can be used as a replacement for sour cream in many dip recipes.

Field Beans

Field beans are *Phaseolus* species and are harvested as mature dry seeds, as opposed to green beans that are harvested for their edible pods. The market classes of field beans include kidney beans, navy beans, pinto beans, black beans, cranberry beans, and great northern beans (Table 20-2). Beans were one of the earliest domesticated crops. Evidence indicates they may have been domesticated in southern Mexico and Central America as well as in the Andean region of South America over 7000 years ago. They were likely domesticated about the same time as corn. They were traded among Native Americans and were grown throughout North America prior to colonization by Europeans. The high protein content and viny growth habit of field beans were a good complement to corn, and these beans were often grown together with corn. The diverse size and color was in part due to continued human selection. North Dakota, Michigan, Nebraska, Idaho, and Minnesota are leading states for field bean production.

Description and Adaptation

Field beans have an upright bushy or viny growth habit (Figure 20-5). They have a pinnately compound leaf with three leaflets. Pods are borne in the leaf axils. The pods and seeds of the different types of field beans vary in color and size (Figure 20-6). Field beans are warm-season, summer-annual crops that grow best at low humidity. They prefer fertile soils with good drainage. Like soybean, high temperature and moisture stress during flowering can greatly reduce yields. Field beans are usually harvested by windrowing the vines or bushes, drying them in the field, then combining the windrows.

TABLE 20-2

U.S. acreage and yield of edible dry beans in 2009. *Adapted from USDA-NASS (2010).*

	Total area		Average yield	
Market class	in acres	in hectares	in lb/acre	in kg/hectare
Pinto	654,600	264,907	1667	1868
Navy	186,500	75,474	1787	2003
Black	179,300	72,560	1679	1882
Light red kidney	52,400	21,206	1845	2068
Great northern	48,300	19,546	2068	2318
Dark red kidney	47,300	19,142	1797	2014
Cranberry	5400	2185	1556	1744
Dry edible beans, total*	1,463,000	592,055	1733	1942

*Includes all of the above market classes plus blackeye, chickpea, lima, pink, small red, small white, mung, and others.

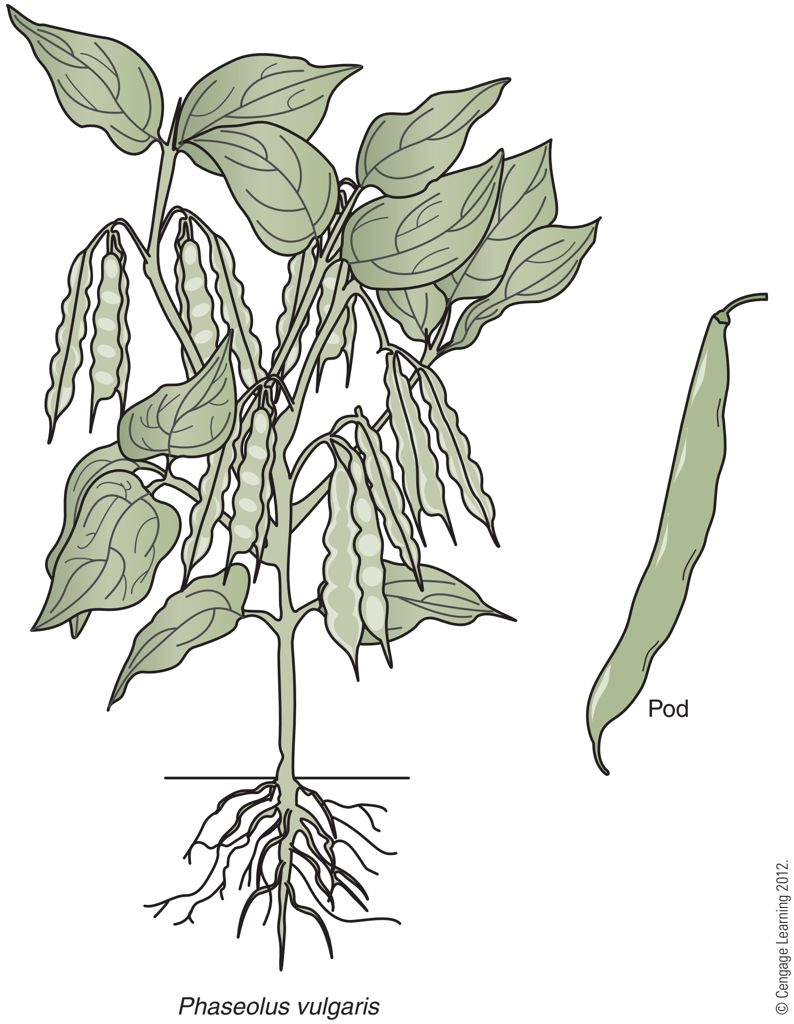


FIGURE 20-5
Field bean is a general name that applies to beans grown for their edible grain. Kidney, pinto, navy, and great northern are all types of field beans.



FIGURE 20-6
Field beans come in a variety of shapes, sizes, and colors.

Use

Field beans are consumed mostly by humans, but they also can be used as livestock feed. They are sold dried or canned and are prepared in chili dishes, baked beans, soups, and as refried beans. Two issues are related to the use of field beans in human diets. The first issue is that bean seeds contain an inhibitor that prevents the trypsin enzyme from digesting protein. Therefore, beans need to be cooked to denature this enzyme, or the protein will be unavailable to humans. The second problem is related to long-chain sugars (oligosaccharides: raffinose and stachyase) in beans. These sugars are rapidly fermented by bacteria in the intestines and result in the subsequent release of carbon dioxide, methane, and hydrogen sulfide. This results in discomfort and foul-smelling flatulence. An enzymatic product sold under the trade name *Beano* digests the oligosaccharides before they reach the intestine, greatly reducing the severity of the problem.

Peanuts

Peanuts (*Arachis hypogaea*), also called *groundnuts*, are native to South America and were an important food and ceremonial crop for earlier Americans. Their use spread throughout the tropical and subtropical regions. Peanuts were brought to Europe, Africa, and Asia by the Spanish and Portuguese. They were introduced into North America from Africa. Georgia produces more than 40 percent of the U.S. peanut crop. Texas, Alabama, Florida, and North Carolina also have significant peanut acreage.

Description and Adaptation

The peanut is a low-growing annual plant (Figures 20-7 and 20-8). The peanut plant has prostrate-to-upright stems that sometimes reach a height of 18 inches (46 centimeters). It has a pinnately compound leaf with two pairs of leaflets. Yellow flowers are borne in leaf axils of the stems. The peanut is unique because after pollination, the ovary elongates to produce a **peg** that buries the ovary into the soil. The ovary then matures and hardens into a shell containing the peanuts (Figure 20-9).

The peanut grows best in tropical and subtropical climates that have warm growing-season temperatures, adequate rainfall, and a long growing season. Peanut production is favored in well-drained, sandy soils that allow for formation of the peanut. Peanuts are grown in the southern United States from Florida to Oklahoma. Peanuts are also important rotational crops utilized in West Africa and India where they are rotated with pearl millet and sorghum, and in Southeast Asia where they are rotated with cassava and rice. The four general types of peanuts are Runner, Virginia, Spanish, and Valencia.

Use

The peanut is dug, extracted, processed, and consumed as a snack food, peanut butter, and a candy. Over half of the peanut crop grown in the United States is consumed as peanut butter. The peanut can also be pressed to extract oil that is

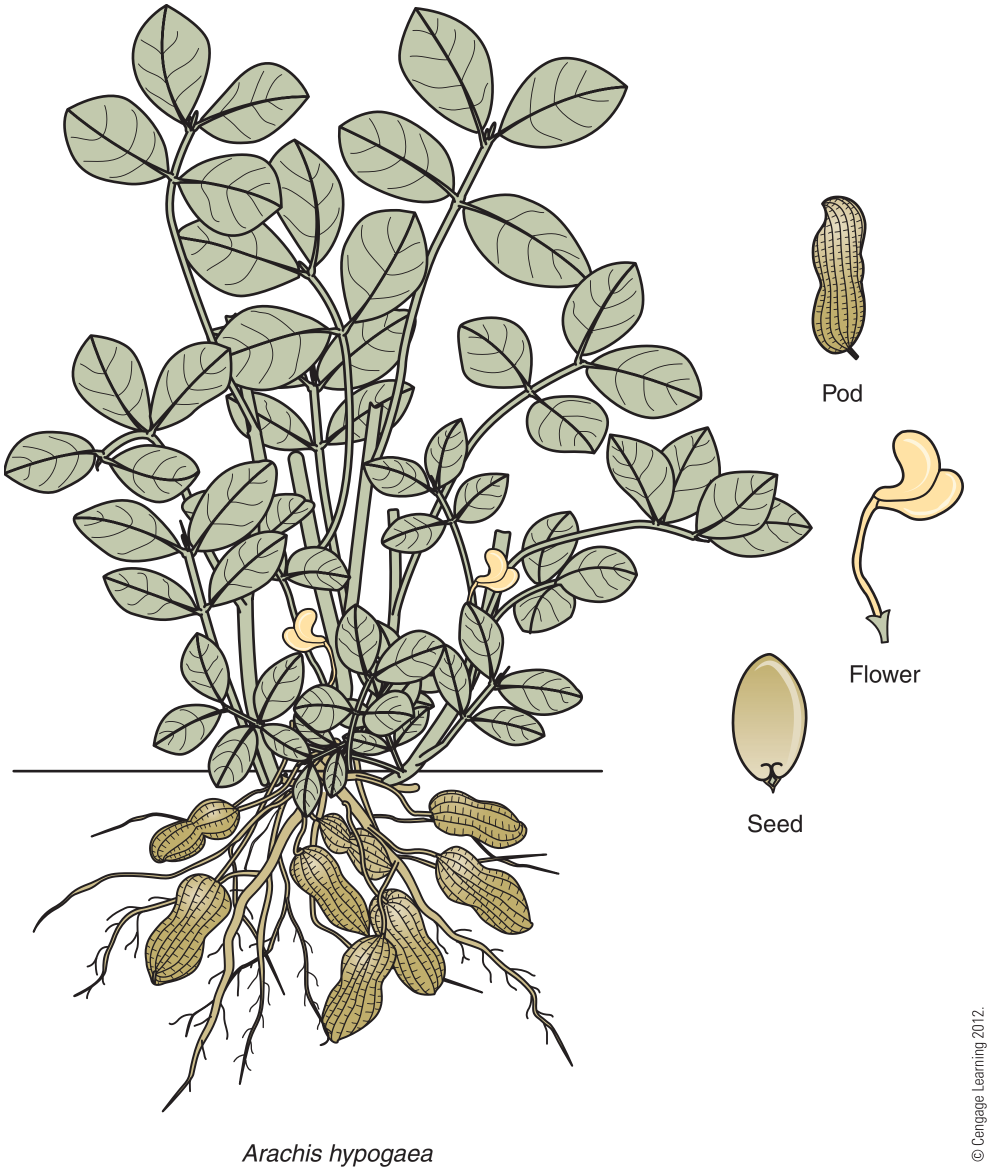


FIGURE 20-7
Peanut plant showing the development of the pods below ground.

used for margarine, salad dressings, and cooking oil. After oil extraction, the remaining peanut cake is fed to livestock. The majority of worldwide production is used for extraction of oil. Industrial uses for the peanut include paint and cosmetics. The rhizoma (perennial) peanut (*Arachis glabrata*) is used as a forage legume for grazing and as a hay crop, and it has been planted as a cover crop.

One issue with the use of peanuts for human food is the peanut allergy. Some individuals have severe allergic reactions to tiny amounts of peanut, and these reactions can result in anaphylactic shock. All products that have been processed on machinery with peanuts (and other nuts) must be labeled to avoid accidental consumption by peanut-allergy sufferers.



FIGURE 20-8
The peanut plant has an odd pinnate leaf arrangement and bright yellow flowers.



FIGURE 20-9
Several types of peanuts.

Field Peas

Field peas (*Pisum sativum*) are native to western Asia and were domesticated up to 9000 years ago in the Fertile Crescent. They have been an important human food source since the beginning of agriculture. Peas were introduced into the United States by European colonists for use as both a food and livestock feed. Idaho, North Dakota, Washington, Oregon, and Montana are the leading states for field-pea production in the United States today (Table 20-3). Canada, Russia, and India are the largest producers of field peas worldwide. Most of the field pea production

TABLE 20-3

Field pea production in the United States, 2009. *Adapted from USDA-NASS (2010).*

State	Total area		Yield	
	in acres	in hectares	lb/acre	kg/hectare
Idaho	41,000	16,592	1900	2130
Montana	226,000	91,459	1330	1491
North Dakota	480,000	194,249	2400	2690
Oregon	5900	2388	2240	2511
Washington	85,000	34,398	2000	2242
U.S. total	837,900	339,086	2045	2292


Craig Sheaffer, University of Minnesota.

FIGURE 20-10
Field pea in flower.

in the United States is used as dried peas for soup or for livestock feed. Field peas may be grown in a mixture with small grains as a forage crop, for hay, pasture, or silage.

Field peas are planted in early spring and grown as summer annuals in the Midwest and mature before the onset of hot weather. Peas grow best with an average temperature of 55–65°F (13–18°C). In the Pacific Northwest, peas are also grown as winter annuals and planted in September. Peas have an upright, viny growth habit (Figure 20-10). They have an even pinnate leaf arrangement with tendrils. Pea varieties typically have yellow-, green-, and cream-colored seed. Varieties of field pea with cream-colored seed are most commonly grown for the consumer market.

Other Pulse Crops

There are several other legumes that are used as grains, including the following.

Lentil

Lentil (*Lens culinaris*) is a cool-season, annual legume native to southern Asia. Lentils are an important human food crop dating back to the beginning of domesticated agriculture and are even mentioned in the Bible. They yield best under low rainfall conditions. Lentil is a semierect, short plant with tendrils and pinnate leaves yielding small pods with one to two seeds per pod (Figure 20-11). It is grown primarily in Europe, North Africa, West Asia, Canada, and in the Pacific Northwest. Lentil is a high-protein grain that is mostly used for human food. The whole or split seeds are eaten in lentil soups or stews, ground into flour, and utilized for the edible pods.

Lupine

Lupine (*Lupinus* sp.) is native to the Mediterranean region. There are many species, but white, yellow, and blue lupines are grown as crops. Lupine is a high-protein (32–38%) grain crop that can be fed to poultry, swine, and cattle. It is adapted to well-drained, low pH soils. It is not tolerant of wet soils. Lupine is not widely grown because soybean, its major competitor, is more profitable.

Chickpea

Chickpea (*Cicer arietinum*), also known as *garbanzo bean*, is a short-stature legume grown for its edible seed that is an important food source for human consumption in Asia, the Middle East, North Africa, and especially India where it is used in a



George Vandemark, USDA-ARS.

FIGURE 20-11
Lentils.

variety of dishes. It originated in Turkey and was domesticated up to 8500 years ago. It is a cool-season, annual crop. The two main types of chickpeas produced worldwide are "desi" and "kabuli." India produces over 80 percent of the world's chickpeas. Its acreage in the United States is limited, but it is very popular in India and other Asian countries. The dried seeds are cooked or boiled. The seeds are also ground for flour, eaten green like peas, and the green pods and shoots are eaten as a vegetable.

Faba Beans

Faba beans (*Vicia faba*), also known as *fava beans*, *horse beans*, *broad beans*, *pigeon peas*, or *Windsor beans*, are a warm-season, temperate, annual crop native to Northern Africa and West Asia. It is one of the world's oldest cultivated vegetable crops. Along with chickpeas and lentils, faba beans have been an important human food source in the Mediterranean since ancient times. China is the world's largest producer of them today, with other important production centers in Egypt, Ethiopia, and Morocco. The plant grows upright to heights of 2 to 5 feet tall (0.6 to 1.5 meters) and has an indeterminate flowering habit with pods forming on the stems. They are consumed fresh or dried as shelled beans and sold frozen or canned.

Cowpeas

Cowpeas (*Vigna unguiculata*) are also called *black-eyed peas* and were domesticated in Central Africa up to 6000 years ago. They were subsequently brought to the United States during the European colonization in the 1700s. They are an important annual warm-season food legume in hot and drought-prone regions of the tropics and have an indeterminate flowering habit. Cowpeas are grown largely in Africa, with some minimal production in the southern United States. Cowpeas can be ground into flour, or be sold whole in dry, canned, or frozen forms. All parts of the plant can be eaten as a vegetable. The green plant is also utilized as animal forage.

Alfalfa

Alfalfa (*Medicago sativa*), also called *lucerne*, is one of the oldest, cultivated forage crops. Alfalfa originated in the Near East and was used as a livestock feed by the Persians, Aravians, Greeks, and Romans. The word *alfalfa* was derived from an Iranian word meaning *horse fodder*. Seed of alfalfa was spread throughout the world by conquering armies who carried forage for livestock feeding and by traders. Alfalfa forage and seed were introduced into the colonies in the mid-1700s, and a century later into the southwestern United States and California by the Spanish. The first winter-hardy type of alfalfa was brought into Minnesota by a German immigrant, Wendelin Grimm. A variety, Grimm, was at one time the most widely grown winter-hardy alfalfa in the north central region. Additional introductions into the United States and Canada occurred from Peru, India, Africa, France, and

TABLE 20-4

Alfalfa production of the top five states in alfalfa acreage. *Adapted from USDA-NASS (2010).*

	Total area		Yield		Value
State	in acres	in hectares	tons/acre	tonnes/hectare	$
South Dakota	2,500,000	1,000,000	2.3	5.2	462,875,000
North Dakota	1,780,000	700,000	1.9	4.1	232,157,000
Montana	1,700,000	690,000	2.1	4.7	342,720,000
Wisconsin	1,550,000	620,000	2.5	5.6	375,875,000
Minnesota	1,300,000	530,000	3.0	6.7	436,800,000
U.S. total	21,227,000	8,600,000	3.4	7.5	7,997,221,000

Russia. These plants that were first introduced have been improved through plant breeding. Selection for traits such as disease resistance and insect resistance are important for its widespread use. Alfalfa varieties have been developed that vary in fall-dormancy reaction and winter survival. In northern regions, dormancy in response to short days and reduced temperatures is important for winter survival of the plant. In California, where winters are generally milder, dormancy is less important and nondormant alfalfa varieties with high yield potential are grown. In addition to improvement in alfalfa varieties, alfalfa use has been promoted through development of soil fertility and harvest management recommendations that support establishment and persistence.

Alfalfa is the most widely grown forage legume in the United States and Canada, where more than 20 million acres (8 million hectares) are grown. The leading states of harvested alfalfa acreage in 2009 are shown in Table 20-4. In addition, there are areas devoted to alfalfa seed production in California and other western states. Seed production is highly specialized, requiring isolation of fields and dedicated pollinating insects such as the alfalfa leaf cutter bee.

Description and Adaptation

Alfalfa is an herbaceous, perennial legume that, in most humid environments, is grown for 3 to 5 years. In some dry areas with fewer diseases, alfalfa plants have persisted for more than 15 years. Alfalfa's persistence is related to its tolerance to low temperatures. In colder northern latitudes, alfalfa undergoes a pronounced winter dormancy period and regrows from an enlarged crown each spring. Alfalfa will have from two to five regrowth cycles per growing season. Mature alfalfa plants have about 20 stems, which on average reach a height of 2 feet (0.6 meter; Figure 20-12). Leaves are predominately pinnately trifoliolate and are arranged alternately on the stem.

Alfalfa has a large taproot that in mature plants can reach a depth of 20 feet (6 meters). The taproot and crown of alfalfa are storage sites for starch and are critical for its persistence. Starch is used for energy during dormant periods and for energy for regrowth in the spring and following cutting. Like most legumes,

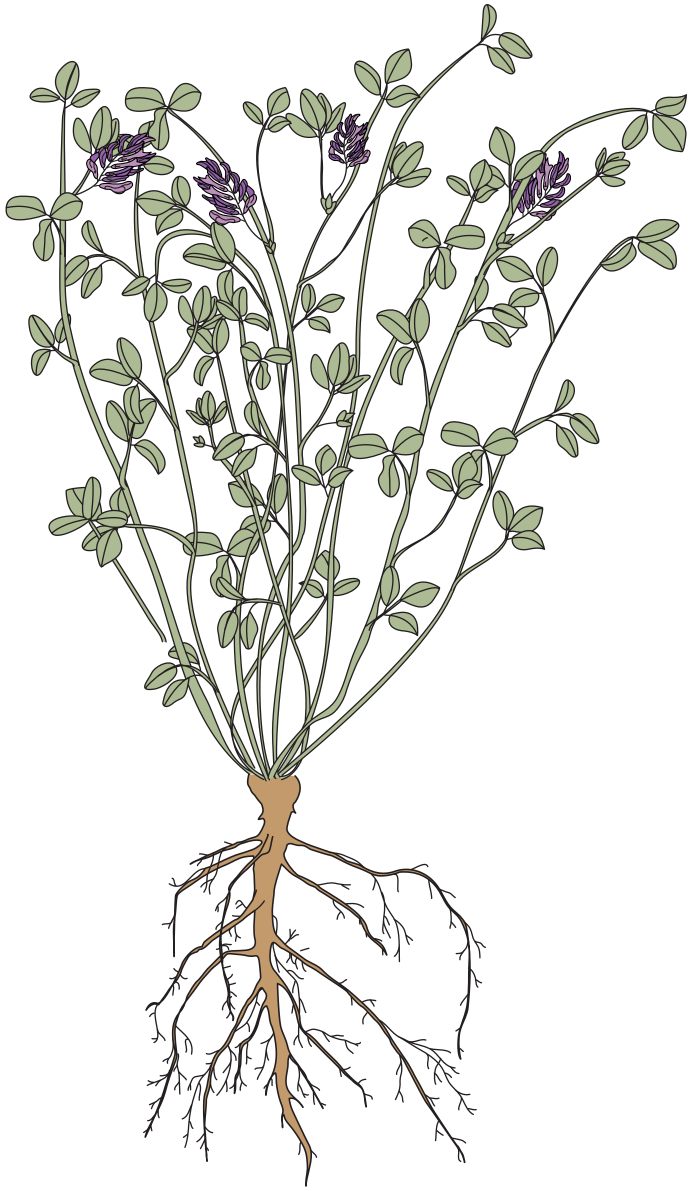


FIGURE 20-12
Alfalfa.

alfalfa has the potential to conduct biological nitrogen fixation. On most soils, alfalfa can obtain more than 50 percent of its nitrogen from biological nitrogen fixation and can contribute some to subsequent crops in the rotation.

Alfalfa establishes and grows best on soils with a neutral pH and moderate to high levels of soil nutrients such as P and K. Soil fertility is especially important under stressful harvest management. Alfalfa is also very intolerant of wet, poorly drained soils.

Use

Alfalfa is mostly harvested and used as hay and silage. It is used to a lesser extent in grazing systems. Alfalfa forage is high in protein and a good source of fiber in ruminant rations. Relative to grasses, it has high intake potential. However, careful management is required for grazing ruminant animals such as sheep and cattle, because bloat can develop. **Bloat** occurs because high soluble carbohydrate and protein levels in the leaves entrap gases in the rumen, forming a froth. As a result, belching of gases cannot occur, and the rumen swells. Ultimately, the animal dies of suffocation (due to compression of the lungs) and internal hemorrhaging.

Alfalfa is often grown in mixture with perennial grasses such as smooth bromegrass, orchard grass, or timothy. Growing alfalfa-grass mixtures can increase drying of alfalfa hay, reduce incidence of alfalfa bloat, increase alfalfa winter hardiness, and provide yield if stands of one of the species declines.

Average yields can be as high as 10 tons/acre (22 tonnes/hectare) under irrigation in California, to about 6 tons/acre (13 tonnes/hectare) in the midwestern United States. Seed yield in California averages about 700 pounds/acre (127 kilograms/hectare). Alfalfa is also valued as a component of crop rotations with nonlegumes such as corn. A good stand of alfalfa can supply all the nitrogen-fertilizer needs of a subsequent corn crop. Alfalfa also is used as a source of nectar for honey production.

Many potential new, nonfeed uses for alfalfa require additional research. These include its use as a protein source for human diets, a source of fermentable energy for ethanol production, and a source of fiber for papermaking.

Other *Medicago* Species

Medicago falcata is a yellow-flowered perennial alfalfa that is native to Siberia. It is very cold-hardy and has been used for pasture in dryland regions. There are also more than 100 annual species (called *annual medics*) of *Medicago* that are native to the Mediterranean region, which has mild, wet winters and hot, dry summers. In that region, they are used as winter annuals, germinating in the fall and maturing and setting seed in the spring before the onset of summer. In pastures, the seed can be consumed by grazing livestock or left to regenerate with the onset of fall rains. Some types of medics are currently used in winter-annual pastures in Texas and California. Improved types of medics have been selected for forage and seed production under dryland conditions in Texas. The genomics of *Medicago truncatula* is being studied to provide a better understanding of alfalfa genetics. Black medic, *Medicago lupulina*, is being used in Montana as a nitrogen source in small grain cropping systems.

Other Forage Legumes

Like alfalfa, many other legumes are valued for production of protein-rich forage for livestock feed. They often have lower yield potential than alfalfa but may have better adaptation to specific harvest management or soil conditions than alfalfa. However, many legumes do not adapt to a wide range of environmental conditions

as grasses do. Therefore, their use is restricted to specific regions. Some examples include the following:

True Clovers

Clovers (*Trifolium* spp.) are grown on considerable acreage. Within this genus are perennial and annual species. All *Trifolium* species have compound leaves with three leaflets (trifoliolate), and they differ in leaf shape and stem characteristics (Figure 20-13). The trifoliums have potential to conduct biological nitrogen fixation, have a high-protein and high-fiber forage, and produce their seed in small pods. Though alfalfa may be the most widely grown and productive legume when grown on fertile soils, the clovers are more adaptable to a diversity of soils and climates.

Some examples of true clovers include red clover, white clover, kura clover, crimson clover, and berseem clover.

Red clover (*Trifolium pratense*) is a short-lived perennial used for hay, silage, and pasture in the northern United States. Red clover is often a substitute for alfalfa on soil with low pH and low fertility. It has an upright, hairy stem with a dark red-purple flower color. The individual flowers are grouped together in a round-oblong inflorescence, also called a *head*.



FIGURE 20-13 White clover. This diagram shows some of the traits of the true clovers, including the head inflorescence, trifoliolate leaves, and stolons.

White clover (*Trifolium repens*) is a short-lived, cool-season, perennial forage legume (Figure 20-14). It can persist by reseeding and by spreading with its short stolons. White clover is shallow rooted and has poor tolerance to heat and drought; therefore, in the North, it is productive in the spring and fall; in the South and West, where drought stress can occur, it is productive in the late winter and early spring. There are tall- and short-growing forms of white clover; the short form is more adapted to close grazing and frequently volunteers in pastures and lawns. White clover is used mostly as a pasture legume and is frequently grown with perennial grasses.

Kura clover (*Trifolium ambiguum*) is a perennial, forage legume adapted to the northern United States. Kura clover has a very deep taproot that allows it to tolerate extreme drought and has rhizomes that enable it to spread vegetatively



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FIGURE 20-14
White clover plants.

(Figure 20-15). It has greater winter hardiness than all other forage legumes and it is tolerant of abusive grazing. In contrast to most other forage legumes, kura clover was introduced in the early twentieth century and research on it has been limited. Varieties need to be developed with greater seedling vigor and greater seed production.

Crimson clover (*Trifolium incarnatum*) is the most widely grown annual forage legume in the United States. It is an erect, annual legume that has herbage covered with soft hairs. In spring it bears an oblong, bright crimson-colored flower (Figure 20-16). Crimson clover is grown as a winter annual as it has poor heat- and moisture-stress tolerance. Crimson clover is used as a pasture and hay crop in the South, and as a cover crop in both the North and the South. In the South, it is often overseeded into warm-season, perennial grass pastures. Reseeding varieties of crimson clover have been developed that produce seed in the spring for later regeneration in the fall.

Berseem clover (*Trifolium alexandrinum*) is an important crop in the Mediterranean and is therefore also called *Egyptian Clover*. Berseem clover is a winter-annual legume with oblong leaflets and hollow stems. It grows upright and produces yellowish-white flowers in the spring. Berseem clover is grown as a winter annual and has the same uses as crimson clover. Berseem clover produces more fall and winter growth than do the other winter-annual clovers.



Craig Sheaffer.

FIGURE 20-15
Kura clover.



FIGURE 20-16
Crimson clover derives its name from its crimson red inflorescences.

Birdsfoot Trefoil

Birdsfoot trefoil (*Lotus corniculatus*) can be harvested for hay and silage, but because of its weak stems, it is ideally suited for use as pasture. Birdsfoot trefoil can provide good nutrition for grazing animals because its protein is less readily broken down by microbes in the rumen. Birdsfoot trefoil is a short-lived perennial with many fine stems. Its leaves consist of five leaflets, three grouped together at the end of the petiole and two at the petiole base near the stem. The species derives its common name from the claw-like arrangement of cylindrical seed pods (Figures 20-17 and 20-18). It tolerates wet soils and can withstand several weeks of flooding. It grows best at neutral soil pH, but it tolerates acidic soil, high alkalinity, and salinity. Birdsfoot trefoil has been widely used for conservation and beautification plantings along highways. However, birdsfoot trefoil can be invasive and disturb native prairies. When uncut, it flowers continuously, producing a large amount of small seed that can be washed or windblown into adjacent areas.

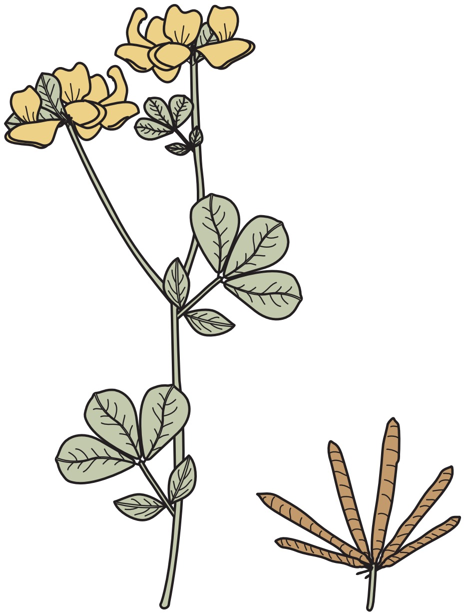


FIGURE 20-17
Diagram of birdsfoot trefoil showing stem, leaves, flower, and pod.



FIGURE 20-18
Birdsfoot trefoil flowers and seed pods.

Sweet Clover

Sweet clover (*Melilotus* spp.) is not widely cultivated as a harvested forage crop, but is still planted for soil conservation. It frequently volunteers as a weedy species along roadsides, pastures, and rangelands. It was once widely used as a fertilizer nitrogen source in crop rotations before inexpensive commercial nitrogen fertilizer became available. When not harvested, it produces more nitrogen for plow

down than any other legume. It is also used for honey production. Sweet clover is a biennial plant that has a deep, penetrating taproot that is responsible for its soil-improvement benefits and ability to survive drought and cold. It produces a high percentage of hard seed that can survive in soil for more than 20 years; this aids in its ability to regenerate, following death of the parent plant. High coumarin levels in sweet clover cause a bitter taste to which livestock become accustomed. If hay from sweet clover is not dried properly and becomes moldy, the coumarin is converted to dicoumarol (see Chapter 4).

Vetches

Vetches (*Vicia* spp.) are annuals that produce trailing vines with tendrils. They are grown as winter or summer annuals in temperate areas of the world for green manure and forage. They are an excellent green manure crop because they maintain a higher nitrogen percentage at plant maturity than other legumes. Hairy (*V. villosa*) and common vetch (*V. sativa*) are the most widely cultivated species.

Sainfoin

Sainfoin (*Onobrychis viciifolia*) is a perennial legume adapted to the dry soils of the western United States where the soil pH is neutral. It has erect, hollow stems that bear pinnately compound trifoliolate leaves. Sainfoin is used as a hay and pasture legume. Sainfoin does not tolerate frequent defoliolation.

Native Forage Legumes

North America has many native, prairie legume species that may in the future be used agronomically alongside the more traditional legumes. Benefits of using native legumes include their natural adaptation as well as their increasing the diversity of crops we grow. One especially promising native legume is Illinois bundleflower (*Desmanthus illinoensis*), a shrub-like perennial. Its range includes the tallgrass and short-grass prairie regions from North Dakota to Texas. This species is used in range revegetation programs and is an important food plant for wildlife. Its forage quality is similar to domesticated forages and it also has potential as a grain crop. Researchers are examining other native legumes for use as forages, including: false indigo (*Amorpha fruticosa*), Canada milkvetch (*Astralagus canadensis*), showy tick trefoil (*Desmodium canadense*), purple prairie clover (*Dalea purpurea*), downy milkpea (*Galactia volubilis*), prairie acacia (*Acacia angustissima*), showy partridge pea (*Chamaecrista fasciculata*), American vetch (*Vicia americana*), and lead plant (*Amorpha canescens*). These species are also being used in prairie restorations and Conservation Reserve Program (CRP) plantings.

Review Questions

1. Describe the legume family and name the important crops from this family.
2. What makes soybeans important, and what are some of the different uses for soybeans?
3. What are field beans, and what are they used for?
4. Describe some of the uses of peanuts. Why are some people not able to consume peanuts?
5. Identify two other grain legumes besides beans or peanuts that are less widely grown, but still important to human nutrition.
6. What is a forage legume? Give an example.
7. Describe the alfalfa plant.
8. What is alfalfa used for?
9. Identify another forage legume and its specific use.
10. Compare the different species of true clovers. Which one appears to be most adapted to your area?

Critical Thinking

1. Compare the nutritional value of grain from a legume such as soybean and a grass such as wheat. How are they similar, and how do they differ?
2. Review the information presented in Chapter 8 dealing with biological nitrogen fixation. How much nitrogen can a legume such as soybean or alfalfa fix? How does this reduce the nitrogen fertilizer requirement of corn growing in rotation?
3. Consult Chapter 17 and outline how a legume such as alfalfa is made into hay.
4. For your state or an adjoining state, go to an agricultural website and determine the grain and forage yield potential of important forage and grain legume crops.

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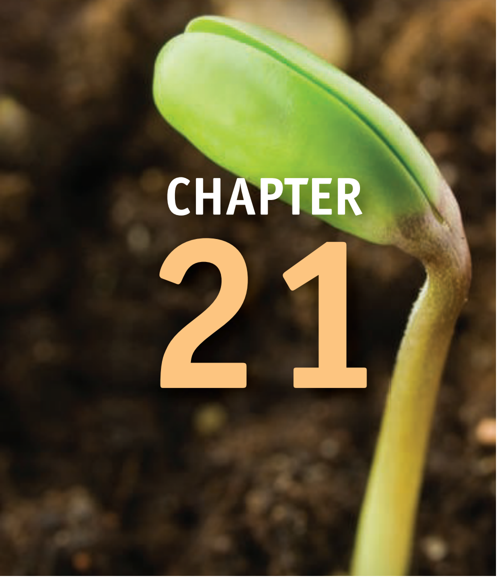
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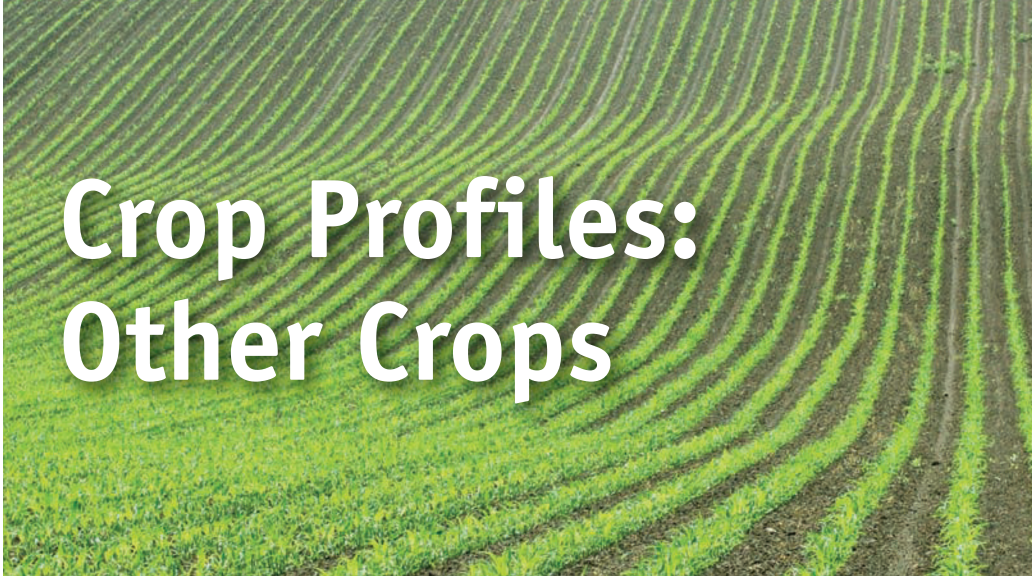
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CHAPTER 21



Crop Profiles: Other Crops





Key Concepts

- The potato is grown for tubers that contain starch. It is among the five most important food crops in the world.
- Sweet potato is a starchy root crop unrelated to potato.
- Yam, cassava, turnip, and Jerusalem artichoke are other food crops grown for root or tuber starch.
- Tobacco is the most economically significant drug crop grown in the United States.
- Sugar crops are crops grown specifically for production of sugar and include sugar beet, sugarcane, corn, and sweet sorghum.
- Sugar beet and sugarcane are used for production of table sugar.
- Plant fibers from cotton, flax, and hemp are used for making paper, clothing, rope, and baskets.
- Soybean, sunflower, safflower, canola, and cotton seed are used for oil production.

Key Terms

alkaloid
cane
canola
cassava
corn
cotton
eye
flax
hemp
Jerusalem artichoke
linseed oil
opium poppy
plantain
potato
safflower
sisal
sugar beet
sugarcane
sunflower
sweet potato
sweet sorghum
taro
tobacco
tuber
turnip
yam

Introduction

In addition to the grasses and legumes, there are many other widely used crops in other plant families that are significant food sources or that have economic significance. These include crops that produce starch, sugar, fiber, drugs, and oils.

Starchy Root Crops

Starchy root crops are important energy sources in diets throughout the world. Potatoes, sweet potatoes, yams, cassava, and turnips are from a diversity of plant families and are significant energy sources in human diets.

Potatoes

The **potato** (*Solanum tuberosum*) originated in the Andean highlands of South America, and the early civilizations in that region used it as a food source. For example, it was an important food source for the mighty Incan civilization. The Spanish explorations of South America in the 1500s resulted in the potato's introduction into Europe. It became established as an important dietary staple, especially among the poor. In Ireland, the population depended heavily on the potato as a food source. The susceptibility of Irish potatoes to late blight of potato (*Phytophthora infestans*) resulted in the catastrophic Irish potato famine in the 1840s. Europeans introduced the potato into North America in the 1600s. The potato is an important human food crop in the United States today and worldwide. Along with wheat, rice, corn, and barley, it is among the crops with the greatest annual production. Russia and China are the leading producers. Idaho and Washington produce almost 50 percent of U.S. potatoes. Wisconsin, Colorado, North Dakota, and Minnesota also have significant potato production.

More than half of the U.S. potato crop is processed into frozen french fries and other frozen, reconstituted potato products, as well as potato chips. The remainder is purchased fresh and consumed as baked, mashed, and fried potatoes. Some producers also specialize in production of seed potatoes. Unlike many other crops that are planted from seed, most commercial production of potatoes uses seed potatoes that are small, whole tubers or tuber pieces containing eyes.

The potato plant is a bushy plant with many fleshy stems 1–3 feet (0.3–0.9 meter) long (Figure 21-1). With maturity, the stems frequently lodge. The stems contain large, pinnately compound leaves. Plants have flowers that are white or various shades of purple (Figure 21-2). Potatoes store energy as starch in enlarged underground stems called **tubers**. Tubers contain numerous **eyes**, which are dormant buds. Four main types of potato are most widely grown: russet white, round red, round white, and long white. In addition, some of the many other types of potato marketed today as fresh potatoes include white, purple, and yellow fingerlings, as well as yellow- and purple-fleshed round potatoes (Figure 21-3). Fresh potato tubers contain about 25 percent carbohydrates and less than 3 percent protein. They contain little fat or cholesterol unless deep fried or served with margarine, butter, or sour cream.

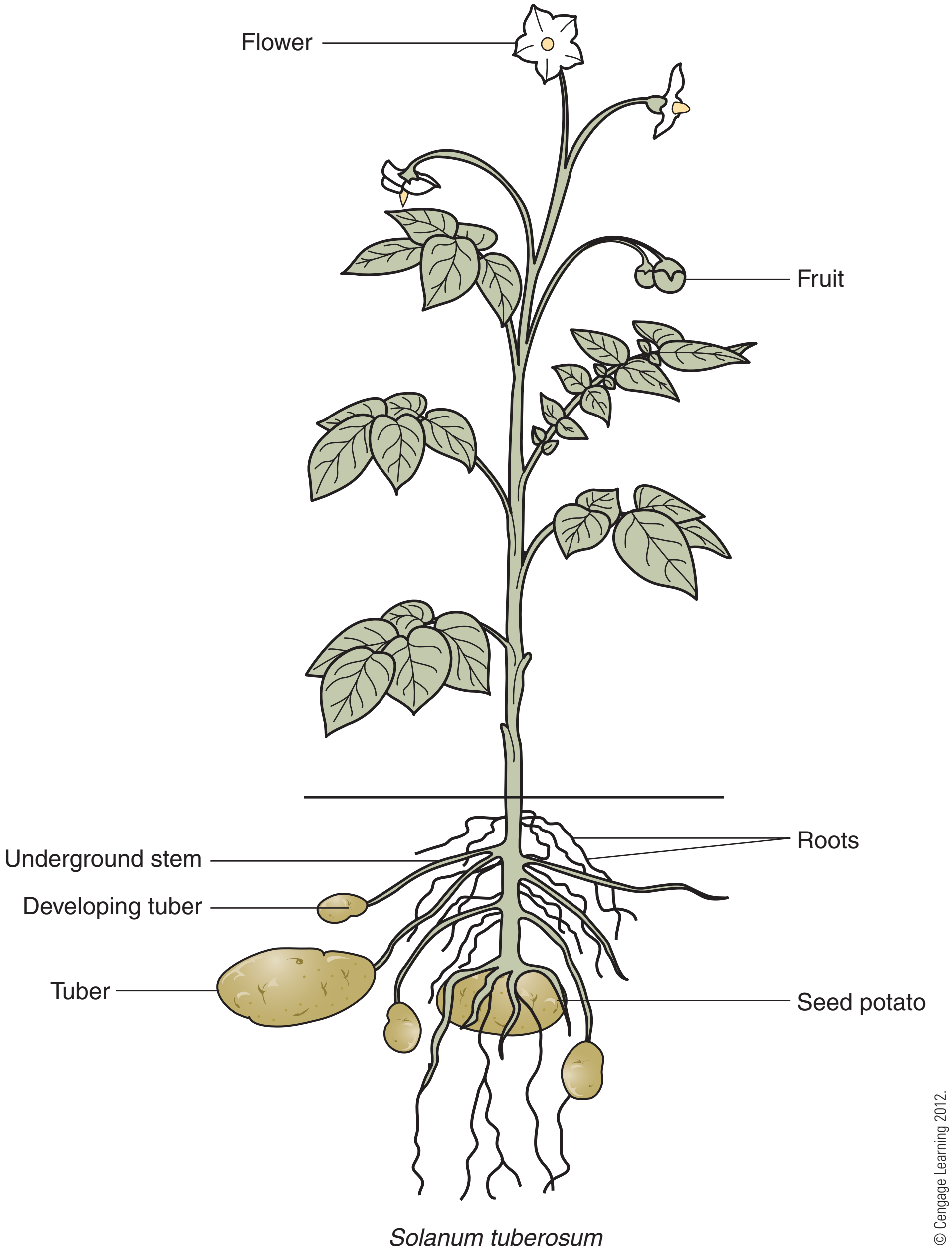


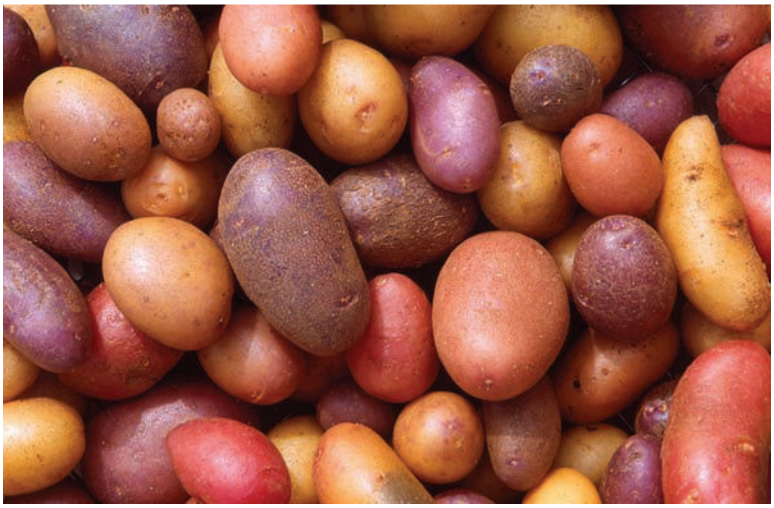
FIGURE 21-1
The potato plant.

The potato belongs to the nightshade family that, in addition to potato, includes tobacco, nightshade, tomato, pepper, and belladonna. Like other members of the Solanaceae family, potatoes contain alkaloids in the stems and leaves. Potatoes that are exposed to sunlight and turn green also contain **alkaloids**. The potato alkaloid, solandine, reduces the palatability of tubers and can be toxic if consumed in high quantities. Peeling green potatoes removes the alkaloid.



David L. Hansen, University of Minnesota.

FIGURE 21-2
The flower color of the potato plant is dependent on cultivar. They can be purple or white.



Scott Bauer, USDA-ARS.

FIGURE 21-3
Potatoes come in a variety of shapes, sizes, and colors.

The potato is best adapted to cool environments with average growing-season temperatures of about 70°F (21°C). Tuber production is reduced by temperatures above 85°F (30°C). Excessive moisture can cause tubers to rot. Today, many potatoes are produced on light-textured, sandy soils with irrigation as needed. Potatoes are mostly grown as a summer annual in northern latitudes (e.g., Idaho, Maine, and Minnesota), and as a fall, winter, or spring annual for planting in states such as Florida or California (Table 21-1).

TABLE 21-1

Potato acreage and yield by seasonal group in 2009. *Adapted from USDA-NASS (2010).*

Seasonal group (when harvested)	Total area		Average yield		Top producing states
	acres	hectares	lb/acre	kg/acre	
Spring	73,700	29,800	28,900	32,000	Florida
					California
					North Carolina
Summer	43,000	17,400	33,600	37,700	Missouri
					Virginia
					Texas
Fall	920,000	372,000	42,800	48,000	Idaho
					Washington
					North Dakota
Winter	8700	3500	24,500	27,000	California

Sweet Potatoes

Sweet potato (*Ipomoea batatas*) originated in the tropical areas of Central and South America and was widely grown by the native people as a dietary staple. It was domesticated about 5000 years ago. Sweet potato was also cultivated in the Pacific Islands. Columbus encountered the sweet potato in the Caribbean and introduced it into Spain. Worldwide, sweet potato is among the top-10 food crops. China and other Asian countries are the leading producers. Sweet potato production in the United States is centered in the southern states with over one-third of national production centered in North Carolina. Sweet potato is consumed by humans and livestock and, in some countries, it is also fermented to produce alcohol. It belongs to the morning glory family (Convolvulaceae) and is not related to the potato (nightshade family).

The sweet potato is a viny plant with trailing stems 4–16 feet (1–5 meters) long (Figure 21-4). The leaves are heart shaped. It has large, showy, white flowers with a corolla that can be up to 2 inches (5 centimeters) wide. The sweet potato stores energy in a modified root (unlike potato, which stores energy in a modified stem). Each plant produces 3 to 12 storage roots per plant. Like the potato, the sweet potato stores energy as starch, but it also contains sugar, which results in its sweet taste. Sweet potato roots vary in color from white to orange. Two types of sweet potatoes are grown most often in the United States: a yellow-flesh type that is dry and starchy, and an orange-flesh type that is sweet and moist. The orange type of sweet potato is favored in the southern United States. In the United States, sweet potato fields are established by planting small-rooted seedlings.

Sweet potato is a tropical species that grows best where average air temperatures exceed 80°F (27°C). It is subject to chilling injury at air temperatures less than 50°F (10°C). It is grown as an annual in the United States, but in tropical areas it is grown as a perennial.

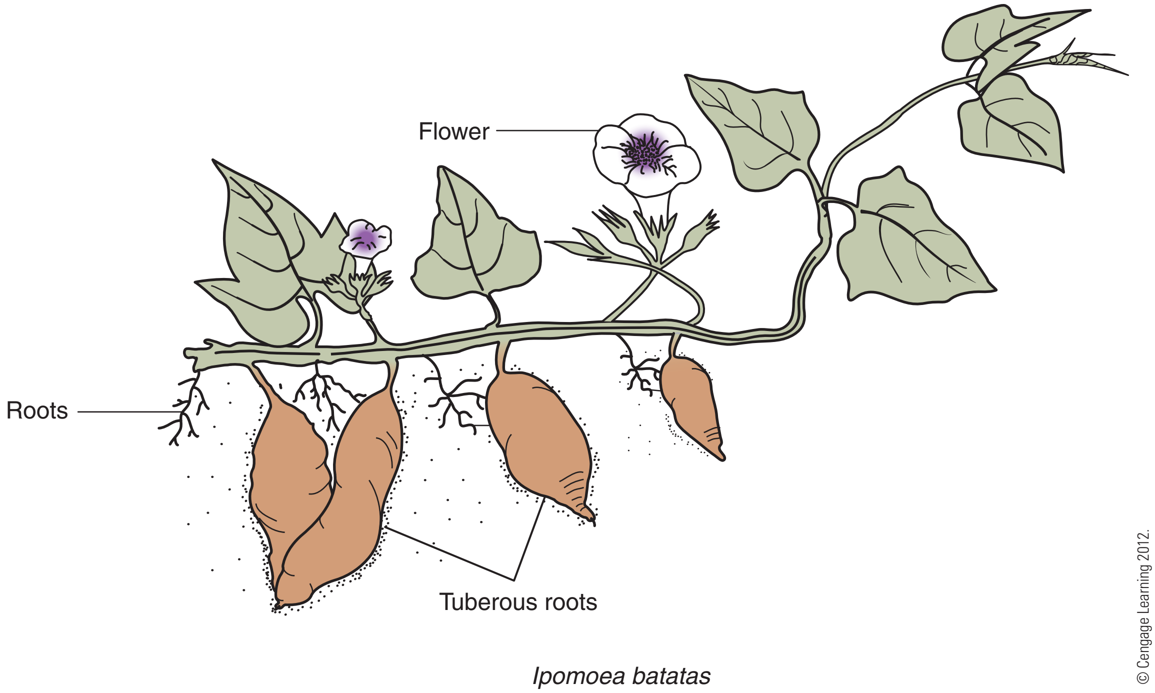


FIGURE 21-4 The sweet potato plant.

Cassava

Cassava (*Manihot esculenta*), also known as *manioc*, *tapioca*, and *yucca*, is a tropical native of Brazil and Central America and is one of the few edible members of the spurge family (Euphorbiaceae). The Portuguese brought cassava to West Africa in the 1500s and South Asia in the 1700s. It is the fourth primary source of caloric intake for people in the tropical climates of Brazil and Africa following rice, sugar, and corn. Cassava is a perennial, woody shrub with palmately compound leaves. Cassava plants have 5 to 10 large, fleshy roots. The roots contain about 30 percent starch and a small amount of protein and oil. Cassava is particularly well adapted to the humid tropics with high rainfall and can grow on poor or exhausted soil with little additional management. In subsistence agriculture, it is often interplanted with corn, peanuts, bananas, and coconut.

Sweet or bitter types of cassava vary in their cyanogenic glycoside content. Bitter varieties contain cyanogenic glycosides that convert to hydrogen cyanide (HCN), a potent poison in the human digestive system. HCN is removed by methods that include drying, soaking, boiling, dehydrating, and fermenting.

The roots are processed into many different steamed, fried, boiled, and dried foods, depending on the local culture. The cassava mush is also used to make beer. Tapioca is produced from cassava roots and used as a thickening agent for making desserts; it is usually the only form of cassava eaten in the United States. Cassava is also utilized for the production of paper and other industrial materials.

Other Starch Crops

There are several other starchy crops grown throughout the world including true yams, plantains, taro, turnip, and Jerusalem artichoke.

True Yams

True **yams** (*Dioscorea* spp.) are native to the tropics with independent domestication occurring in Africa, Asia, and South America. Most of the yams grown today come from the "yam region" of West Africa, from Cameroon to the Ivory Coast. Although they store energy below ground like potato or sweet potato, they are a distinct species. Over 60 separate species are cultivated for their edible tubers with *D. cayenensis*, *D. rotundata*, *D. trifida*, and *D. alata* being the most important. Yams are twining, viny plants that, like potatoes, store energy in swollen stems (tubers). They are perennial plants grown as annuals and plants are often staked for maximum production. The plants are propagated vegetatively by tuber cuttings. Tubers are harvested by hand and vary in size. They can be the size of a potato or grow much larger, up to 100 pounds (45 kilograms). Like cassava, most yams are consumed locally and are not traded on the global market. The energy and protein content of yams is similar to that of the potato.

"Fufu" is a traditional, West African dish composed of mashed and boiled yams that are eaten with meats, vegetables, or stews. Other methods of preparation include boiling, roasting, or frying.

Plantains

Plantains (*Musa* spp.) are a tropical starch crop related to the common banana. They originated in tropical Malaysia and subsequently spread to the South Pacific and Southeast Asia. They are grown and eaten throughout the tropics, but most of the world production is located near the equator in West and Central Africa. The plantain "tree" is actually a tree-like, herbaceous perennial with a pseudostem made up of overlapping leaf petioles. The plants are propagated vegetatively from suckers or cuttings. Plantains are sometimes grown as a shade crop for important, understory species such as coffee and cacao.

The starchy ripe and green fruits are primarily consumed locally and are often eaten boiled, roasted, or fried. In addition, the plantain plant is utilized as fiber for thatching, rope, fabric, shoes, and other products. Plantains are also fed to livestock.

Taro

Taro (*Colocasia esculenta*) is a tropical plant native to India and Malaysia that began to be cultivated around 7000 years ago. The plant spread from South Asia to Africa where it was brought to tropical America by the slave trade. Taro is a perennial, herbaceous plant grown as an annual for its starchy corm. It is grown in most tropical areas worldwide as a locally consumed crop, because the corms do not store well. The crop is propagated vegetatively using pieces of the corm for production. The taro plant has air passages in its tissue that allow the plant to survive flooding. Similar to rice production, taro can be grown under flooded production systems or in areas with high rainfall or irrigation. In the United States, Hawaii is the only state with significant taro production (Figure 21-5).



USDA-NRCS.

FIGURE 21-5
Harvesting taro in Hawaii.

Taro cannot be eaten without being processed due to toxic levels of calcium oxalate, which must be removed by cooking or steeping. The starch-filled corm is generally eaten boiled, roasted, or baked. An important staple dish in Hawaii is cooked and fermented taro, called *poi*. Taro is being replaced by rice as a cultivated crop in tropical climates.

Turnip

Turnip (*Brassica rapa*) and rutabagas (*Brassica napobrassica*) are members of the Brassica family. They are temperate, cool-season, root crops native to Europe. Turnips are biennials that produce seed in the second growing season; when used as a food crop their root is harvested during the seeding year. They have considerable cold tolerance and are often grown as winter annuals. They were some of the earliest domesticated crops and were brought to the Americas by the original colonists. Turnips and rutabagas contain starch in their roots and can be cooked and consumed like potatoes.

Jerusalem Artichoke

Jerusalem artichoke (*Helianthus tuberosus*) is a perennial native to North America. It resembles the sunflower except that the heads are only about 2 inches (5 centimeters) in diameter. It stores energy in tubers as inulin, a fructose polymer. Tuber yields from the Jerusalem artichoke can be as high as 5 tons/acre (11 tonnes/hectare). Native Americans and the colonists used the tubers of Jerusalem artichoke as an energy source. They have a limited retail market in the United States today. Because of their high, simple sugar content, Jerusalem artichoke tubers can be fermented to alcohol.

Drug Crops

In the United States, there are few crops dedicated for drug production (at least legally). Tobacco, however, is one drug crop that is economically significant.

Tobacco

Tobacco (*Nicotiana tabacum*), like potato, is a member of the Solanaceae family. Tobacco is not grown as food for humans or feed for livestock, but rather as a drug crop. Native Americans originally domesticated the plant as a medicinal, sacred, and ceremonial crop up to 3000 years ago. Tobacco was considered the first cash crop of the American colonies, and its export to meet growing demand in Europe was vital to the survival of the early English settlements in Virginia, where it was introduced in 1612. Additionally, the widespread cultivation of tobacco fueled the slave trade in the new American colonies. Economically, tobacco is one of the top-10 crops in the United States, which is the fourth-largest producer behind China, Brazil, and India. In 2009, tobacco was harvested from about 350,000 acres (142,000 hectares), yielding a total of about 800 million pounds (363 million kilograms).

Description and Adaptation

Tobacco is an herbaceous annual growing from 3 to 5 feet (1 to 1.5 meters) with simple leaves (Figure 21-6). The tobacco plants are nearly always transplanted into prepared fields due to the small seed size. Growers prevent flowering, fruiting, and lateral branching of this crop, unless it is being grown for seed (Figure 21-7). In addition, shade cloths are sometimes used to encourage the formation of broad, thin leaves. Each plant can produce 30 or more leaves. The leaves of tobacco are harvested by hand as they mature, mainly for cigar production, or by machine that cuts the entire stalk. They are then dried, either by air, heat, sun, or smoke (called *curing*), graded, then fermented or aged. The lowest leaves of the tobacco plant can be harvested in as little as 2–3 months.

Two tobacco species dominate commercial cultivation today; *N. tabacum*, about 90 percent of production, and *N. rustica*, about 10 percent of production. Specific types of tobacco are grown depending on how it will be used in the final product. Types include Burley, Brightleaf (or Virginia), shade, Perique, and Oriental. Most tobacco products utilize a blend of different tobacco varieties. The top states for tobacco production are North Carolina, Kentucky, Virginia, Tennessee, South Carolina, and Georgia.

Use

Humans use tobacco for its stimulating drug effects. These effects can be obtained by either smoking, chewing, or snorting the different forms of tobacco that include cigars, cigarettes, chew, pipe tobacco, and snuff. Air-cured



FIGURE 21-6
A farmer in his tobacco field in Virginia.

tobacco is used primarily for cigars; fire-cured tobacco is used for pipe and chewing tobacco, while flue-cured and sun-cured tobaccos are utilized for making cigarettes. Though cigarettes are the most common form of tobacco consumed today worldwide, they were not widely popularized in the United States until the mid-1900s after the invention of a cigarette-making machine. Nicotine, one of the alkaloid compounds found in tobacco, is primarily responsible for the stimulating and addictive properties. Nicotine is a neurotoxin that has been used as an insecticide in the past. The use of tobacco is a factor in many health problems including lung cancer, heart disease, emphysema, and mouth cancer.



Bob Nichols, USDA-NRCS.

FIGURE 21-7
Tobacco crop being topped (flowers removed) on a North Carolina farm.

Opium poppy

Opium poppy (*Papaver somniferum*) is a drug crop that was first domesticated about 5000 years ago in the Middle East. It is likely the first medicinal plant that was domesticated. Today, it is a source of both legal and illegal drugs. The sap is called opium and contains numerous opiate alkaloids such as morphine and codeine, which are legal narcotics used as painkillers in the United States. Opium can be further processed to make heroin, an illegal drug in the United States. Heroin was first introduced to the United States in 1898 as a pain-relieving drug, but its addictiveness later led to it being banned.

The opium poppy is an annual plant that grows 3–4 feet (0.9 to 1.2 meters) tall. It is grown for sap contained within its seed capsules. It has attractive flowers in an assortment of colors, and it is also grown as an ornamental plant (Figure 21-8). Opium poppy is adapted to warm, dry climates and can be grown as a summer or winter crop. It generally does not require irrigation or substantial fertilization. Three to four months after planting, the sap can be extracted from the capsules. Similar to tapping a maple tree for syrup, the capsules are sliced by hand and the latex sap is allowed to drip before being collected by hand into containers. Capsules can be sliced multiple times over several days. Harvest occurs before the capsule is fully mature; after ripening the alkaloids begin to break down. The raw opium sap is dried and formed into bricks.

After latex harvest is complete, the capsules can be dried and seed can be collected. Opium poppy is also the source for poppy seeds, which are used for culinary purposes such as baking and for oil.

Most of the world's opium for heroin is grown in Afghanistan, but Columbia and Mexico are also sources for heroin in the United States. Pharmaceutical sources of opium poppy are grown in Australia, India, and Turkey for morphine and codeine.

Opium poppy has significant economic and political associations. The economies of several developing countries, particularly Afghanistan, are dependent



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FIGURE 21-8
An opium poppy plant.

upon it. Politically, opium production has been a problematic issue for the United States in its war in Afghanistan. It is grown instead of food crops because it is often the most profitable option. The opium trade is purported to partially finance the terroristic acts of the Taliban in Afghanistan, but many poor Afghan farmers could not live without the income from opium.

Sugar Crops

Sugar crops are crops grown specifically for production of sugar, the disaccharide composed of glucose and fructose in equal proportions. Sugar beet, a member of the Chenopodiaceae (goosefoot family), and sugarcane, a member of the Poaceae

(grass family), are the leading sugar crops in the world. In the United States about 60 pounds (27 kilograms) of sugar, mostly from sugar beet, are consumed per person per year.

Sugar Beet

The **sugar beet** (*Beta vulgaris*) was selected from the fodder beet in the 1700s. This white-rooted beet originally had a sugar content of about 5 percent. Additional selection by French scientists greatly improved its sugar content. The French emperor Napoleon encouraged this development to provide a reliable source of sugar for France if the British blockade prevented the import of cane sugar. The sugar beet was introduced into the United States in the early 1800s and today is used for production of table sugar and other domestic and industrial uses. Minnesota, North Dakota, and Idaho produce more than 67 percent of the sugar beets. Smaller acreages are grown in California, Montana, and Michigan. Because of the cost associated with the transport of the bulky root, sugar beet processing usually occurs within the production region. Most of the production and processing is controlled by grower-owned cooperatives.

Sugar beet is a biennial plant that is grown as an annual for sugar production. In the first year, the plant produces a root and a basal rosette of large, oblong leaves (Figure 21-9). Sugar beets have a large, cone-shaped white root terminating in a taproot. Roots typically weigh about 10 pounds (4.5 kilograms) when harvested in the fall after spring planting. The sugar beet contains from 18–20 percent sugar



FIGURE 21-9
The sugar beet plant.

when harvested. Sugar beet growth and harvest is carefully monitored by growers to maximize sugar yield per acre. By-products of sugar processing such as the pulp and molasses can be used as livestock feed and beet leaves can be used as silage. For seed production, the plant must overwinter and flower the year after seeding. Sugar beet production is adapted to regions with average summer temperatures of about 70°F (21°C). Temperatures above 80°F (27°C) retard sugar accumulation in the root.

Sugarcane

Sugarcane (*Saccharum officinarum*) is native to the South Pacific region and India. Columbus brought sugarcane to the Caribbean Islands on his return trips to the region in 1493. It subsequently was propagated throughout the tropical and subtropical regions of South America and became an important export crop to Europe. It was first grown in North America by the French about 1750. High labor demands associated with harvesting and processing of sugarcane led to enslavement of first the Native Americans and later Africans.

Sugarcane is best adapted to humid, tropical regions, and world production is centered in South America, Cuba, and Africa. Sugarcane provides only a small portion of the U.S. sugar production, but more than 50 percent of the world's sugar production. A small amount is still produced in Louisiana, Florida, Texas, and Hawaii.

Sugarcane is a tall, perennial grass growing up to 20 feet (6 meters) tall. It is a C_4 plant and is extremely efficient in sugar production. It has thick, fleshy stems from 3–5 inches (8–13 centimeters) in diameter (Figure 21-10). The **canes** (stems) usually contain from 12–15 percent sucrose. The canes are crushed to extract the sugar. The residue (bagasse) can be used as a biofuel or for making wood products. Sugarcane plantations are propagated vegetatively by planting stem sections that produce adventitious roots and shoots from the nodes. Because sugarcane is perennial, plantings can be harvested several times, but eventually fields must be replanted as yields become lower with successive harvests.

Other Sugar Crops

Corn (*Zea mays*) is a leading source of sugar in the United States. It provides about 50 percent of the sweetener in the form of traditional corn syrup or high fructose corn syrup. Starch in the grain is converted to sugars (see Chapter 19).

Sweet sorghum (*Sorghum bicolor*) varieties are grown for the high stem sugar content. The sugar is extracted by crushing the stem. Historically, sweet sorghum was once an important sweetener source in colonial America. Sweet sorghum sugar and syrup are used in several products, and there is interest in developing sweet sorghum as an ethanol crop. Sweet sorghum has the potential to yield 200 gallons or more of ethanol per acre (1870 liters per hectare).



FIGURE 21-10
Sugarcane plant showing leaves, stems, and inflorescence.

Fiber Crops

Plant fibers have been critical for human cultures. Plant fibers, in addition to animal skins, provided the first clothing for humans and are important for making paper, rope, and baskets. Cotton is the leading fiber plant in the world. Other

plants that provide fiber include flax and hemp. The development of synthetic fibers for multiple uses has reduced our reliance on plant fibers.

Cotton

Cotton (*Gossypium hirsutum*) was independently domesticated and used for clothing in Asia (India) and in Central and South America from 4000 to 5000 years ago. It was cultivated in ancient Africa, Babylonia, and China. There is a diversity of *Gossypium* species harvested for cotton. Cotton species originating in the Americas (upland cotton) have longer fiber lengths than those from Asia (sea-island cotton). The majority of cotton grown today is upland cotton. Cotton was cultivated in southern colonies beginning in the early 1600s and became a profitable export crop based on slave labor. The invention of the textile mill and the cotton gin, which mechanically separated the cotton fibers from the seed, significantly increased production and fueled European demand for cotton, which in turn, promoted the American slave trade. Cotton production, especially the harvest, was an extremely labor-intensive process that only subsided after the advent of mechanical pickers and harvesters in the mid-twentieth century.

Natural fiber color is primarily white, but green, brown, orange, and red colors are produced from some varieties. At maturity, cotton bolls (the seed-bearing capsules) open and expose a cottonly mass of fiber. The fibers are hairs that arise from the seed coats of each of the 10–40 seeds in every boll. Each seed can have as many as 20,000 seed hairs. The seed hairs are either long (lint) or short and firmly attached to the seed (fuzz). Cotton is widely used for the production of textiles and clothing. It is often mixed with synthetic fibers as a blend. Texas produces nearly 30 percent of the U.S. cotton. It is also produced in Mississippi, California, Georgia, and Arkansas. Economically, it is one of the top five crops in the United States (see Table 2-8 in Chapter 2).

In the United States, cotton is an annual plant growing from 3 to 5 feet (0.9–1.5 meters) tall (Figure 21-11). In tropical regions, some native cotton


David Nance, USDA-ARS.

FIGURE 21-11
Field of cotton.

grows as tree-like perennials. As an annual, cotton typically has a main stem from which branches arise. The plant has a deep-growing taproot and large, three-lobed leaves. Cotton produces seed in a capsule or boll that is divided into four or five sections. The fibers of cotton are attached to the seed within each section. Once the cotton bolls mature, a defoliant is sprayed on the cotton plants to drop the leaves, and the cotton is either stripped from the stem or picked as it ripens. The cotton fibers are ginned, graded, carded, combed, and spun into yarn. The lint is primarily woven into textiles and clothing. It is often mixed with synthetic fibers as a blend. The fuzz is made into upholstery, mattresses, carpets, cotton balls, and many other products. Cotton seed, a by-product of cotton fiber production, is crushed to extract the oil. The seed residue or meal is used as a livestock feed.

Cotton is a tropical crop that grows best at summer temperatures from 90°F to 95°F (32–35°C). Little growth occurs below 60°F (16°C) or above 100°F (30°C). It requires a growing season of at least 150 days for maturity. Cotton is grown in regions with predictable rainfall or under irrigation.

Flax

Flax (*Linum usitatissimum*) is probably the oldest plant fiber used for making fabric. It was cultivated in Mesopotamia and ancient Egypt nearly 7000 years ago. The early Egyptian culture used flax to produce paper and linen cloth. The cloth was used for garments and also for wrapping mummies. Flax was grown in the American colonies and used for fiber and oil production.

Flax is grown for fiber, oil, and for human nutrition. Flax fiber is derived from the phloem fiber cells within the stem. The fiber is extracted from the stem by retting, a process where the plants are soaked in liquid so the fiber can be separated from other components. Today, flax fiber is used for making clothing, tablecloths, drapes, and upholstery. It is used alone or blended with other fibers.

Flax seed contains highly unsaturated oil called **linseed oil** that is used as a water repellent. It is used mostly in paints and varnishes to protect wood. Linseed oil is used in the manufacture of linoleum, a floor covering. Today, there is renewed interest in consumption of flax oil because of its high concentration of an omega-3 fatty acid (linolenic acid), which has health benefits. Flax has also been used as a companion crop for establishment of small-seeded legumes and grasses. It is noncompetitive and provides a return in the year of legume establishment.

Description

Flax is an annual, herbaceous plant that is grown as a summer annual in the North and as a winter annual in the South. Under production, the flax plant typically has one dominant stem that branches at the top (Figures 21-12 and 21-13). Stems grow to a height of 1–3 feet (0.3–0.9 meter). It has a short taproot. The most prevalent flower color is blue. However, some varieties used as ornamentals have pink or red flowers. Flax produces up to eight seeds in a round boll. There are taller and straighter flax varieties developed for fiber production and shorter more branched varieties developed for seed production. Flax is a cool-season, temperate species.

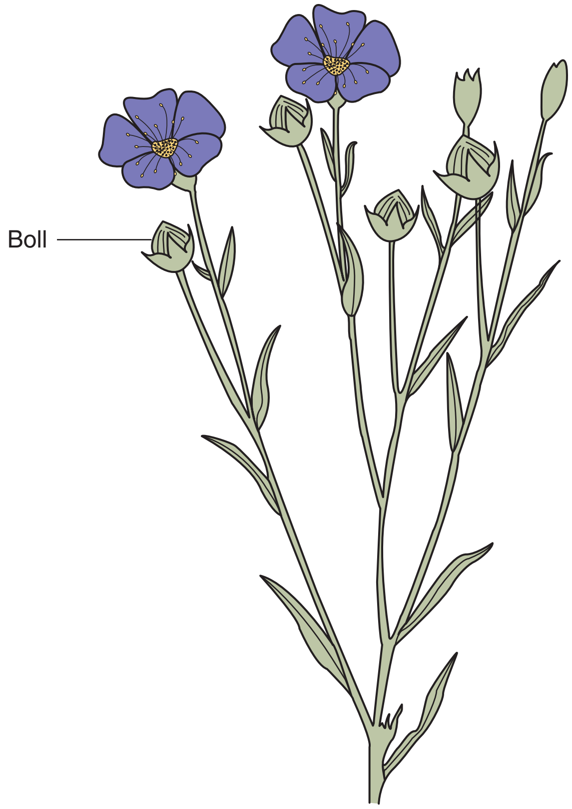


FIGURE 21-12
The seed as well as the stem of the flax plant is used by humans.



FIGURE 21-13
Field of flax.

It does not grow or yield well when subject to temperatures above 85°F (29°C) or moisture stress. The primary production states are North Dakota, Montana, South Dakota, and Minnesota.

Other Fiber Crops

Hemp or marijuana (*Cannabis sativa*) is a tall-growing annual, native to central Asia. It is one of the oldest fiber crops used for cloth, paper, and construction. Hemp fiber is coarse and is most often used for canvas and ropes. It was initially brought into the United States at the beginning of the twentieth century. The fiber is produced from retting of the stem. Hemp is also grown for production of oil and seed for human consumption. The seed is highly nutritious, containing about equal proportions of oil, protein, and carbohydrate. The oil is unsaturated and has a good balance of essential fatty acids. There are several subspecies of hemp. Some are noted for their high levels of tetrahydrocannabinol (THC), a psychoactive chemical. THC and other chemicals in hemp have medicinal potential. Today, hemp is not grown in the United States for fiber; growth and possession of the plant is controlled by the federal government to prevent its misuse.

Sisal (*Agave sisalana*) is a leaf fiber plant native to Central America. The fiber is coarse and used for making twine, floor mats, and rope.

Oil Crops

Most plants produce unsaturated oils that are used for nutrition, cooking, and industrial purposes. Some oils from canola, peanut, and cottonseed are monounsaturated, whereas most others are polyunsaturated. Important oil crops are soybean (see Chapter 20), sunflower, canola, cotton (from seed), and peanut. Soybean produces more than half of the oil consumed in the United States.

Sunflower

Sunflower (*Helianthus annuus*) is a plant native to North America. Wild sunflowers were harvested and later domesticated by Native Americans. It was introduced into Europe by explorers returning from the New World. Wild sunflower plants have many small heads. With domestication, plants with a single, large head were selected. The sunflower was introduced into Europe in the 1600s and it became widely grown in Russia. Russian scientists selected for large seed heads and high oil concentration. Today, sunflowers are produced mostly in North Dakota, South Dakota, Kansas, Colorado, and Texas (Table 21-2).

Specific sunflower varieties are produced for oil and confectionary use. Oilseed sunflowers have black seed, whereas confectionary sunflowers have black- and white-striped seed. Sunflower oil has about 10 percent of the retail oil market in the United States. Oil extracted from sunflower seed is important for use in salad and cooking oil and also in margarine. After processing, one pound (0.45 kilogram) of oilseed-sunflower seed can yield 5.4 ounces (160 milliliters) of

TABLE 21-2

Oil crop acreage and yields for 2009. *Adapted from USDA-NASS (2010)*.

	Total area		Yield		
Oil crop	Acres	Hectare	lb/acre	kg/acre	Top producing states
Sunflower	2,011,300	813,900	1554	1742	North Dakota South Dakota Kansas
Safflower	165,000	66,800	1462	1639	California Montana
Canola	814,000	329,000	1811	2030	North Dakota Oklahoma Idaho

oil. The meal produced after crushing the seed is used for livestock feed. Confectionary sunflowers are also sold as a snack food. Both types of sunflowers are sold for use as wild bird food.

Sunflower is a tall, erect, large-leafed plant that is typically 5 feet (1.5 meters) tall (Figures 21-14 and 21-15). Sunflowers are members of the Asteraceae or Composite family, and the flowers are collected together in a head inflorescence. There are two types of flowers: (1) colorful ray flowers without stamens and pistils surrounding the perimeter of the head, and (2) disk flowers with male and female parts, but without petals, that compose the interior of the head.

Sunflowers are phototropic and, before the flowers are open (bud stage), the buds will turn to and follow the sun. Once the flowers are open, the heads stay pointed toward the east. Sunflowers are a warm-season, annual crop. The optimum temperature for growth is about 75°F (24°C). Sunflowers have moderate tolerance to moisture deficits.

Other Related Species

Like sunflower, **safflower** (*Carthamus tinctorius*) is in the Composite family. It is a short-growing, spiny, annual plant. It is native to the Middle Eastern region that includes Syria, Iran, Iraq, and Jordan. Varieties have been developed to produce unsaturated oil with a high content of either linoleic acid or oleic acid. The oil is used for cooking and commercial purposes. Safflower flowers are used to produce an orange pigment used for dyeing. The seed is also used for feeding birds. California and Montana are the leading states in safflower production (see Table 21-2).

Canola

Canola (*Brassica napus*) is a relatively new crop that produces a polyunsaturated oil for cooking. Canadian plant breeders selected it from oilseed rape. Oil produced from oilseed rape is valued as a lubricant for marine engines. However,

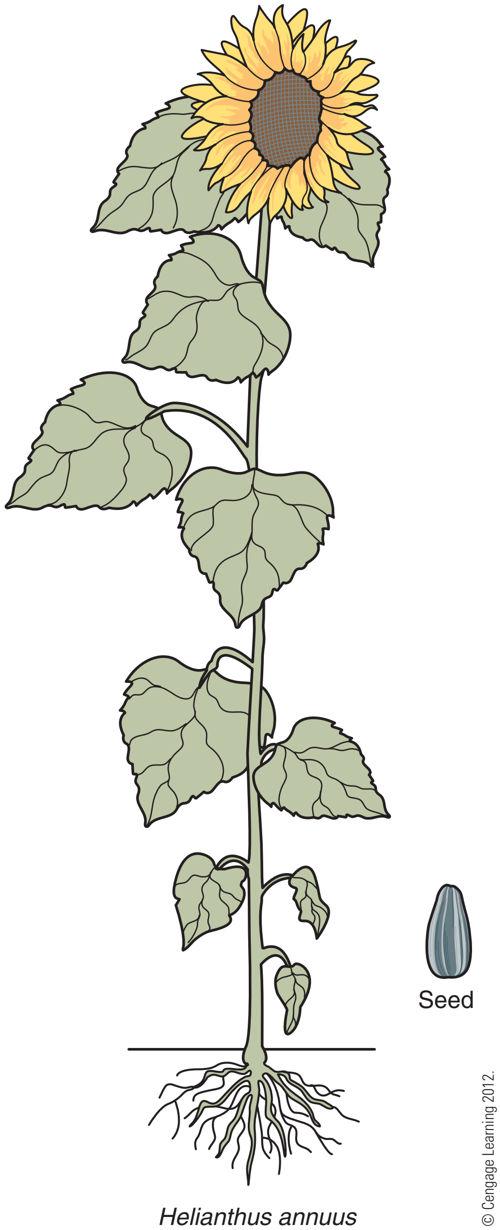


FIGURE 21-14
Sunflower plant.

it contains high concentrations of erucic acid, a poisonous, unpalatable compound. Canola oil, on the other hand, has only low concentrations of erucic acid. Canola is a cool-season, annual member of the Brassica family, which also includes mustard, horseradish, turnip, and forage radish. It is grown as a summer or winter annual. Canola is grown in North Dakota, Minnesota, and Montana (see Table 21-2).

Canola is a multibranched, herbaceous plant that grows from 1–3 feet (0.3–0.9 meter) tall. The individual yellow flowers are arranged in an elongated raceme. Each flower produces many small seeds. The seed contains about 40 percent oil and 23 percent protein. The by-product meal is valuable as a livestock feed.



FIGURE 21-15
The heads of sunflowers generally face the same easterly direction during bloom.

Cotton

Cotton seed is a by-product of cotton fiber. The seed can be crushed and oil is extracted. Cottonseed oil is about 10 percent of the total, domestic oil consumption. The meal is then sold for livestock feed.

Review Questions

1. What are some products made from potato?
2. What are the four most widely grown types of potato?
3. How are potato and sweet potato similar and how are they different in terms of the harvested portion and plant family?
4. Identify two other crops besides potato and sweet potato that produce starchy tubers, corms, or roots.
5. What is the history of the sugar beet, and where is it currently grown in the United States?
6. Identify three crops that are used for producing fiber.
7. Describe what a sunflower plant looks like and identify two foods that are produced by sunflower.
8. Identify three crops that produce oil for human consumption. Refer back to Chapter 6 to identify traits of each plant's oil.
9. For the crops discussed in this unit, indicate their region or country of origin and where they are grown today in the United States.

Critical Thinking

1. In the last three units, we presented brief profiles of a diversity of crops. Did we leave any crops off the list that are important in your state?
2. For a crop that we identified in this section, research the production practices including planting date, fertilization, growing season length, and harvest procedure. Write a short paragraph summarizing your findings.
3. Sugar produced from sugar beet and sugarcane is considered by some to be a more natural product for sweetening beverages than high fructose corn syrup made from corn. Do you agree with that idea? What are the reasons for using high fructose corn syrup instead of sugar from sugar beet or sugarcane?
4. Go to the website for agricultural statistics for your state or the website for the National Agricultural Statistics Service. List the five most important crops for your state and their acreage. What are the important industries for your state?

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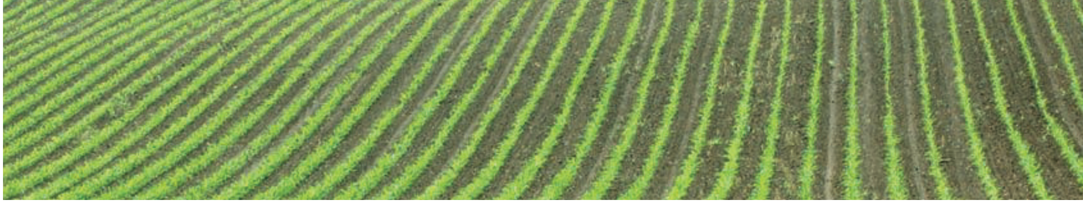
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Appendix 1

Scientific and Common Names

Scientific names allow for the universal identification of all organisms, which are identified using a two-part Latin name, the genus and species.

A. Plants by Scientific Name

Source: USDA-NRCS (2010). *The PLANTS Database*. Baton Rouge, LA: National Plant Data Center. <http://plants.usda.gov> Accessed 30 June 2010.

Scientific name	**Common name**
xTriticosecale rimpaui Wittm.	Triticale
Abutilon theophrasti Medik.	Velvetleaf
Acer spp.	Maple
Achillea millefolium L.	Yarrow
Aconitum napellus L.	Monkshood
Aegilops spp.	Goat grass
Agave sisalana Perrine	Sisal hemp
Ageratina altissima (L.) King & H. E. Robins.	White snakeroot
Agrostis gigantea Roth	Red top
Agrostis spp.	Bentgrass
Alliaria petiolata (Bieb.) Cavara & Grande	Garlic mustard
Allium spp.	Onion
Allium vineale L.	Wild garlic
Aloe vera (L.) Burm. f.	Aloe vera
Amaranthus cruentus L.	Grain amaranth
Amaranthus hypochondriacus L.	Grain amaranth
Amaranthus retroflexus L.	Redroot pigweed
Ambrosia artemisiifolia L.	Common ragweed
Ambrosia trifida L.	Giant ragweed
Ammannia auriculata Willd.	Redstem
Amorpha canescens Pursh	Leadplant
Amphicarpaea bracteata (L.) Fern.	Hog peanut
Andropogon gerardii Vitman	Big bluestem
Arabidopsis thaliana (L.) Heynh.	Mouse-ear cress
Arachis hypogaea L.	Peanut
Artemisia spp.	Sagebrush
Artemisia absinthium L.	Absinthe
Artemisia vulgaris L.	Wormwood

Scientific name	Common name
Asclepias spp.	Milkweed
Asclepias incarnata L.	Swamp milkweed
Asclepias syriaca L.	Common milkweed
Asparagus officinalis L.	Asparagus
Aster spp.	Asters
Aster azureus Lindl.	Skyblue aster
Astragalus canadensis L.	Canadian milk vetch
Avena fatua L.	Wild oat
Avena sativa L.	Oat
Bassia scoparia (L.) A. J. Scott	Kochia
Beta vulgaris L.	Sugar beet
Beta vulgaris var. *crassa* L.	Fodder beet
Betula spp.	Birch
Boehmeria nivea (L.) Gaudich	Ramie
Bouteloua curtipendula (Michx.) Torr.	Sideoats grama
Bouteloua dactyloides (Nutt.) J. T. Columbus	Buffalo grass
Bouteloua gracilis (Willd. ex Kunth) Lag. ex Griffiths	Blue grama
Bouteloua spp.	Grama grass
Brassica napus L.	Canola
Brassica napus var. *napobrassica* L.	Rutabaga
Brassica oleracea L.	Cabbage
Brassica oleracea L. var. *botrytis* L.	Broccoli
Brassica oleracea L. var. *gemmifera* DC.	Brussels sprout
Brassica rapa var. *rapa* L.	Turnip
Brassica spp.	Mustards
Bromus arvensis L.	Bromegrass
Bromus tectorum L.	Cheatgrass
Calamagrostis canadensis (Michx.) Beauv.	Bluejoint grass
Calamagrostis spp.	Reed grass
Camelina sativa (L.) Crantz	Camelina
Camellia sinensis (L.) Kuntze	Tea
Cannabis sativa L.	Hemp/marijuana
Capsella bursa-pastoris (L.) Medik.	Shepherd's purse
Capsicum annuum L.	Pepper
Carduus nutans L.	Musk thistle
Carex vulpinoidea Michx.	Fox sedge
Carthamus tinctorius L.	Safflower
Carya spp.	Hickory
Catharanthus roseus (L.) G. Don	Madagascar periwinkle
Centaurea maculosa Lam.	Spotted knapweed
Cerastium arvense L.	Field chickweed
Chamaecrista fasciculata (Michx.) Greene	Partridge pea
Chenopodium album L.	Lambsquarters
Chenopodium quinoa Willd.	Quinoa
Chondrodendron tomentosum Ruiz & Pav.	Curare vine
Cicer arietinum L.	Chickpea
Cicuta maculata L.	Water hemlock

Scientific name	Common name
Cinchona officinalis L.	Fever bark tree
Cirsium arvense (L.) Scop.	Canada thistle
Cirsium vulgare (Savi) Ten.	Bull thistle
Citrullus lanatus (Thunb.) Matsumura & Nakai	Watermelon
Citrus 3 *paradisi* Macfad. (pro sp.) [*maxima* 3 *sinensis*]	Grapefruit
Citrus 3 *sinensis* (L.) Osbeck (pro sp.) [*maxima* 3 *reticulata*]	Orange
Coffea spp.	Coffee
Colocasia esculenta (L.) Schott	Taro
Conium maculatum L.	Poison hemlock
Coronilla varia L.	Crown vetch
Corylus americana Walt.	Hazelnut (American)
Cucumis melo L.	Cantaloupe
Cucumis sativus L.	Cucumber
Cucumis spp.	Melon
Cucurbita pepo L.	Pumpkin
Curcurbita spp.	Squash
Cuscuta spp.	Dodder
Cynodon L.C. Rich.	Bermuda grass
Cyperus esculentus L.	Nutsedge
Cypripedium spp.	Lady's slippers
Dactylis glomerata L.	Orchard grass
Dalea purpurea Vent.	Purple prairie clover
Dalea spp.	Prairie clover
Datura inoxia Mill.	Moonflower
Datura stramonium L.	Jimsonweed
Daucus carota L. ssp. *carota*	Wild carrot
Daucus carota L. ssp. *sativus* (Hoffmann) Arcang.	Carrot
Desmodium canadense (L.) DC.	Showy ticktrefoil
Digitalis purpurea L.	Purple foxglove
Digitaria eriantha Steud.	Digitgrass
Dioscorea spp.	Yam
Dodecatheon spp.	Shooting star
Echinochloa crus-galli (L.) Beauv.	Barnyard grass
Echinochloa esculenta (A. Braun) H. Scholz	Japanese millet
Eichhornia crassipes (Mart.) Solms	Water hyacinth
Eleocharis dulcis (Burm. f.) Trin. ex Henschel	Water chestnut
Eleusine indica (L.) Gaertn.	Goosegrass
Elymus canadensis L.	Canadian wildrye
Elymus repens (L.) Gould	Quack grass
Epilobium angustifolium L.	Fireweed
Erigeron pubescens Kunth	Hairy fleabane
Erythroxylum coca Lam.	Coca plant
Eucalyptus spp.	Eucalyptus
Eupatorium maculatum L.	Joe-pye weed
Eupatorium perfoliatum L.	Boneset
Euphorbia esula L.	Leafy spurge

Scientific name	Common name
Fagopyrum esculentum Moench	Buckwheat
Ficus carica L.	Fig
Fragaria spp.	Strawberry
Frangula alnus P. Mill.	Glossy buckthorn
Glyceria striata (Lam.) Hitchc.	Fowl manna grass
Glycine max L.	Soybean
Glycine ussuriensis (L.) Merr.	Soybean (wild)
Glycyrrhiza lepidota Pursh	Wild licorice
Gossypium hirsutum L.	Cotton
Helianthus annuus L.	Sunflower
Helianthus maximiliani Schrad.	Maximilian sunflower
Helianthus tuberosus L.	Jerusalem artichoke
Hemarthria altissima (Poir.) Stapf & C.E. Hubbard	Limpograss
Hordeum pusillum Nutt.	Little barley
Hordeum vulgare L.	Barley
Humulus lupulus L.	Hop
Hydrilla verticillata (L. f.) Royle	Hydrilla
Hyoscyamus niger L.	Henbane
Hypericum perforatum L.	St. John's wort
Impatiens capensis Meerb.	Jewelweed
Indigofera tinctoria L.	Indigo
Ipomoea batatas (L.) Lam.	Sweet potato
Iris versicolor L.	Blue flag
Iva annua L.	Marshelder
Koeleria macrantha (Ledeb.) Schult.	Junegrass
Lactuca spp.	Lettuce
Lactuca serriola L.	Prickly lettuce
Larrea tridentata (Sessé and Moc. ex DC.) Coville	Creosote bush
Lens culinaris Medik.	Lentil
Lespedeza capitata Michx.	Round-headed bush clover
Leymus spp. or *Elymus* spp.	Wild rye
Liatris aspera Michx.	Tall blazing star
Linum usitatissimum L.	Flax
Lolium perenne L.	Perennial ryegrass
Lophophora williamsii (Lem. ex Salm-Dyck) J.M. Coult.	Peyote
Lotus corniculatus L.	Birdsfoot trefoil
Lupinus spp.	Lupine
Lycium spp.	Goji berry
Lythrum salicaria L.	Purple loosestrife
Malus spp.	Apple
Malva spp.	Mallow
Mandragora officinarum L.	Mandrake
Manihot esculenta Crantz	Cassava
Medicago falcata L.	Yellow alfalfa
Medicago lupulina L.	Black medic
Medicago sativa L.	Alfalfa
Melilotus officinalis (L.) Lam.	Sweet clover

Scientific name	Common name
Monarda fistulosa L.	Wild bergamot
Musa spp. L.	Banana, plantain
Myriophyllum spicatum L.	Eurasian watermilfoil
Nerium oleander L.	Oleander
Nicotiana spp.	Flowering tobacco
Nicotiana rustica L.	Aztec tobacco
Nicotiana tabacum L.	Tobacco
Olea europaea L.	Olive
Opuntia spp.	Prickly pear
Orobanche spp.	Broomrape
Oryza sativa L.	Rice
Pachira insignis (Sw.) Sw. ex Savigny	Wild Chestnut
Panicum miliaceum L.	Proso (broomcorn millet)
Panicum virgatum L.	Switchgrass
Papaver somniferum L.	Opium poppy
Paspalum dilatatum Poir.	Dallis grass
Paspalum notatum Flueggé	Bahia grass
Pennisetum glaucum (L.) R. Br.	Pearl millet
Pennisetum purpureum Schumach.	Elephant grass
Petunia spp. Juss.	Petunia
Phalaris arundinacea L.	Reed canary grass
Phalaris caroliniana Walt.	Maygrass
Phaseolus vulgaris L.	Field beans
Phleum pratense L.	Timothy
Phoenix dactylifera L.	Date palm
Pinus contorta Dougl. ex Loud.	Lodge pole pine
Pinus ponderosa P. & C. Lawson	Ponderosa pine
Pinus resinosa Ait.	Red pine
Pinus strobus L.	White pine
Pisum sativum L.	Pea, field pea
Poa pratensis L.	Kentucky bluegrass
Podophyllum peltatum L.	Mayapple
Polygonum spp.	Knotweed
Polygonum erectum L.	Erect knotweed
Populus spp.	Aspen
Potentilla arguta Pursh	Prairie potentilla
Prosopis spp.	Mesquite
Prunus americana Marsh.	Wild plum
Prunus serotina Ehrh.	Wild cherry
Pseudotsuga spp.	Douglas fir
Pteridium spp.	Brackenfern
Pueraria montana (Lour.) Merr. var. lobata (Willd.) Maesen & S. Almeida	Kudzu
Quercus spp.	Oak
Ratibida pinnata (Vent.) Barnhart	Yellow coneflower
Rhamnus cathartica L.	Common buckthorn
Rheum rhabarbarum L.	Rhubarb
Rhus glabra L.	Smooth sumac

Scientific name	Common name
Ricinus communis L.	Castor bean
Rubus idaeus L.	Raspberry, wild
Saccharum officinarum L.	Sugarcane
Sagittaria sagittifolia L.	Arrowhead
Salix spp.	Willows
Salsola kali L.	Russian thistle
Salvia divinorum Epling & Jativa	Salvia
Schedonorus phoenix (Scop.) Holub	Tall fescue
Schizachyrium scoparium (Michx.) Nash	Little bluestem
Scirpus litoralis Kuntze	Bulrush
Secale cereale L.	Rye
Setaria italica (L.) Beauv.	Foxtail millet
Silphium perfoliatum L.	Cup plant
Solanum interius Rydb.	Deadly nightshade
Solanum lycopersicum L.	Tomato
Solanum melanocerasum All.	Huckleberry
Solanum melongena L.	Eggplant
Solanum rostratum Dunal	Buffalo bur
Solanum tuberosum L.	Potato
Solidago spp.	Goldenrod
Solidago rigida L.	Stiff goldenrod
Sorghastrum nutans Nash	Indian grass
Sorghum bicolor (L.) Moench	Shattercane
Sorghum bicolor (L.) Moench ssp. *bicolor*	Grain sorghum and sweet sorghum
Sorghum bicolor (L.) Moench ssp. *drummondii* (Nees ex Steud.) de Wet & Harlan	Sudan grass
Sorghum halepense (L.) Pers.	Johnsongrass
Spinacia oleracea L.	Spinach
Sporobolus heterolepis (A. Gray) A. Gray	Prairie dropseed
Stevia rebaudiana (Bertoni) Bertoni	Stevia
Stipa spp.	Needlegrass
Striga spp.	Witchweed
Strychnos nux-vomica L.	Strychnine tree
Taraxacum officinale G.H. Weber ex Wiggers	Dandelion
Taxus brevifolia Nutt.	Pacific yew
Theobroma cacao L.	Cacao (cocoa beans)
Thuja plicata Donn ex D. Don	Red cedar
Toxicodendron pubescens P. Mill.	Poison oak
Toxicodendron radicans (L.) Kuntze	Poison ivy
Tradescantia ohiensis Raf.	Ohio spiderwort
Trifolium alexandrinum L.	Berseem clover
Trifolium ambiguum Bieb.	Kura clover
Trifolium incarnatum L.	Crimson clover
Trifolium pratense L.	Red clover
Trifolium repens L.	White clover
Trillium spp. L.	Trillium
Tripsacum spp.	Gama grass

Scientific name	Common name
Triticosecale rimpaui Wittm.	Triticale
Triticum aestivum L.	Wheat
Triticum aestivum var. *spelta* L.	Spelt
Triticum durum Desf.	Durum wheat
Triticum monococcum L. [excluded]	Eikorn wheat
Triticum turgidum L.	Emmer wheat (Rivet wheat)
Typha spp.	Cattails
Urtica dioica L.	Stinging nettle
Vaccinium macrocarpon Ait.	Cranberry
Vaccinium spp.	Blueberry
Verbena hastata L.	Blue vervain
Vernonia fasciculata Michx.	Ironweed
Veronicastrum virginicum (L.) Farw.	Culver's root
Vicia faba L.	Faba bean
Vicia sativa L.	Common vetch
Vicia villosa Roth	Hairy vetch
Vigna unguiculata (L.) Walp.	Cowpea
Viola spp.	Wood violet
Vitis spp.	Grape
Zea mays L.	Corn
Zea mexicana (Schrad.) Kuntze	Teosinte
Zigadenus venenosus S. Watson	Death camas
Zizania aquatica L.	Wild rice
Zizia aurea (L.) W.D.J. Koch	Golden Alexander

B. Plants by Common Name

Source: USDA-NRCS (2007). *The PLANTS Database*. Baton Rouge, LA: National Plant Data Center. <http://plants.usda.gov> Accessed 19 November 2007.

Common name	Scientific name
Absinthe	*Artemisia absinthium* L.
Alfalfa	*Medicago sativa* L.
Aloe vera	*Aloe vera* (L.) Burm. f.
Apple	*Malus* spp.
Arrowhead	*Sagittaria sagittifolia* L.
Asparagus	*Asparagus officinalis* L.
Aspen	*Populus* spp.
Asters	*Aster* spp.
Aztec tobacco	*Nicotiana rustica* L.
Bahia grass	*Paspalum notatum* Flueggé
Banana	*Musa* spp. L.
Barley	*Hordeum vulgare* L.
Barnyard grass	*Echinochloa crus-galli* (L.) Beauv.
Bent grass	*Agrostis* spp.
Bermuda grass	*Cynodon* L.C. Rich.
Berseem clover	*Trifolium alexandrinum* L.
Big bluestem	*Andropogon gerardii* Vitman
Birch	*Betula* spp.
Birdsfoot trefoil	*Lotus corniculatus* L.
Black medic	*Medicago lupulina* L.
Blue flag	*Iris versicolor* L.
Blue grama	*Bouteloua gracilis* (Willd. ex Kunth) Lag. ex Griffiths
Blue vervain	*Verbena hastata* L.
Blueberry	*Vaccinium* spp.
Bluejoint grass	*Calamagrostis canadensis* (Michx.) Beauv.
Boneset	*Eupatorium perfoliatum* L.
Brackenfern	*Pteridium* spp.
Broccoli	*Brassica oleracea* L. var. *botrytis* L.
Bromegrass	*Bromus arvensis* L.
Broomrape	*Orobanche* spp.
Brussels sprout	*Brassica oleracea* L. var. *gemmifera* DC.
Buckwheat	*Fagopyrum esculentum* Moench
Buffalo bur	*Solanum rostratum* Dunal
Buffalo grass	*Bouteloua dactyloides* (Nutt.) J. T. Columbus
Bull thistle	*Cirsium vulgare* (Savi) Ten.
Bulrush	*Scirpus litoralis* Kuntze
Cabbage	*Brassica oleracea* L.
Cacao (cocoa beans)	*Theobroma cacao* L.
Camelina	*Camelina sativa* (L.) Crantz
Canada thistle	*Cirsium arvense* (L.) Scop.
Canadian milk vetch	*Astragalus canadensis* L.
Canadian wildrye	*Elymus canadensis* L.
Canola	*Brassica napus* L.

Common name	Scientific name
Cantaloupe	*Cucumis melo* L.
Carrot	*Daucus carota* L. ssp. *Sativus* (Hoffmann) Arcang.
Cassava	*Manihot esculenta* Crantz
Castor bean	*Ricinus communis* L.
Cattails	*Typha* spp.
Cheatgrass	*Bromus tectorum* L.
Chickpea	*Cicer arietinum* L.
Coca plant	*Erythroxylum coca* Lam.
Coffee	*Coffea* spp.
Common buckthorn	*Rhamnus cathartica* L.
Common milkweed	*Asclepias syriaca* L.
Common ragweed	*Ambrosia artemisiifolia* L.
Common vetch	*Vicia sativa* L.
Corn	*Zea mays* L.
Cotton	*Gossypium hirsutum* L.
Cowpea	*Vigna unguiculata* (L.) Walp.
Cranberry	*Vaccinium macrocarpon* Ait.
Creosote bush	*Larrea tridentata* (Sessé & Moc. ex DC.) Coville
Crimson clover	*Trifolium incarnatum* L.
Crown vetch	*Coronilla varia* L.
Cucumber	*Cucumis sativus* L.
Cup plant	*Silphium perfoliatum* L.
Curare vine	*Chondrodendron tomentosum* Ruiz & Pav.
Culver's root	*Veronicastrum virginicum* (L.) Farw.
Dallis grass	*Paspalum dilatatum* Poir.
Dandelion	*Taraxacum officinale* G. H. Weber ex Wiggers
Date palm	*Phoenix dactylifera* L.
Deadly nightshade	*Solanum interius* Rydb.
Death camas	*Zigadenus venenosus* S. Watson
Digitgrass	*Digitaria eriantha* Steud.
Dodder	*Cuscuta* spp.
Douglas fir	*Pseudotsuga* spp.
Durum wheat	*Triticum durum* Desf.
Eggplant	*Solanum melongena* L.
Eikorn wheat	*Triticum monococcum* L. [excluded]
Elephant grass	*Pennisetum purpureum* Schumach.
Emmer wheat (Rivet wheat)	*Triticum turgidum* L.
Erect knotweed	*Polygonum erectum* L.
Eucalyptus	*Eucalyptus* spp.
Eurasian watermilfoil	*Myriophyllum spicatum* L.
Faba bean	*Vicia faba* L.
Fever bark tree	*Cinchona officinalis* L.
Field beans	*Phaseolus vulgaris* L.
Field chickweed	*Cerastium arvense* L.

Common name	Scientific name
Field pea	*Pisum sativum* L.
Fig	*Ficus carica* L.
Fireweed	*Epilobium angustifolium* L.
Flax	*Linum usitatissimum* L.
Flowering tobacco	*Nicotiana* spp.
Fodder beet	*Beta vulgaris* var. *crassa* L.
Fowl manna grass	*Glyceria striata* (Lam.) Hitchc.
Fox sedge	*Carex vulpinoidea* Michx.
Foxtail millet	*Setaria italica* (L.) Beauv.
Gama grass	*Tripsacum* spp.
Garlic mustard	*Alliaria petiolata* (Bieb.) Cavara & Grande
Giant ragweed	*Ambrosia trifida* L.
Glossy buckthorn	*Frangula alnus* P. Mill.
Goat grass	*Aegilops* spp.
Goji berry	*Lycium* spp.
Golden alexander	*Zizia aurea* (L.) W.D.J. Koch
Goldenrod	*Solidago* spp.
Goosegrass	*Eleusine indica* (L.) Gaertn.
Grain amaranth	*Amaranthus cruentus* L.
Grain amaranth	*Amaranthus hypochondriacus* L.
Grama grass	*Bouteloua* spp.
Grape	*Vitis* spp.
Grapefruit	*Citrus* 3 *paradisi* Macfad. (pro sp.) [*maxima* 3 *sinensis*]
Hairy fleabane	*Erigeron pubescens* Kunth
Hairy vetch	*Vicia villosa* Roth
Hazelnut (American)	*Corylus americana* Walt.
Hemp	*Cannabis sativa* L.
Henbane	*Hyoscyamus niger* L.
Hickory	*Carya* spp.
Hog peanut	*Amphicarpaea bracteata* (L.) Fern.
Hop	*Humulus lupulus* L.
Huckleberry	*Solanum melanocerasum* All.
Hydrilla	*Hydrilla verticillata* (L. f.) Royle
Indian grass	*Sorghastrum nutans* Nash
Indigo	*Indigofera tinctoria* L.
Ironweed	*Vernonia fasciculata* Michx.
Japanese millet	*Echinochloa esculenta* (A. Braun) H. Scholz
Jerusalem artichoke	*Helianthus tuberosus* L.
Jewelweed	*Impatiens capensis* Meerb.
Jimsonweed	*Datura stramonium* L.
Joe-pye weed	*Eupatorium purpureum* L.
Johnsongrass	*Sorghum halepense* (L.) Pers.
Junegrass	*Koeleria macrantha* (Ledeb.) Schult.
Kentucky bluegrass	*Poa pratensis* L
Knotweed	*Polygonum* spp.
Kochia	*Bassia scoparia* (L.) A. J. Scott
Kudzu	*Pueraria montana* (Lour.) Merr. var. *lobata* (Willd.) Maesen & S. Almeida
Kura clover	*Trifolium ambiguum* Bieb.

Common name	Scientific name
Lady's slippers	*Cypripedium* spp.
Lambsquarters	*Chenopodium album* L.
Leadplant	*Amorpha canescens* Pursh
Leafy spurge	*Euphorbia esula* L.
Lentil	*Lens culinaris* Medik.
Lettuce	*Lactuca* spp.
Limpograss	*Hemarthria altissima* (Poir.) Stapf & C.E. Hubbard
Little barley	*Hordeum pusillum* Nutt.
Little bluestem	*Schizachyrium scoparium* (Michx.) Nash
Lodge pole pine	*Pinus contorta* Dougl. ex Loud.
Lupine	*Lupinus* spp.
Mallow	*Malva* spp.
Mandrake	*Mandragora officinarum* L.
Maple	*Acer* spp.
Marijuana	*Cannabis sativa* L.
Marshelder	*Iva annua* L.
Maximilian sunflower	*Helianthus maximiliani* Schrad.
Mayapple	*Podophyllum peltatum* L.
Maygrass	*Phalaris caroliniana* Walt.
Melon	*Cucumis* spp.
Mesquite	*Prosopis* spp.
Milkweed	*Asclepias* spp.
Moonflower	*Datura inoxia* Mill.
Mouse-ear cress	*Arabidopsis thaliana* (L.) Heynh.
Musk thistle	*Carduus nutans* L.
Mustards	*Brassica* spp.
Needlegrass	*Stipa* spp.
Nutsedge	*Cyperus esculentus* L.
Oak	*Quercus* spp.
Oat	*Avena sativa* L.
Ohio spiderwort	*Tradescantia ohiensis* Raf.
Oleander	*Nerium oleander* L.
Olive	*Olea europaea* L.
Onion	*Allium* spp.
Opium poppy	*Papaver somniferum* L.
Orange	*Citrus* 3 *sinensis* (L.) Osbeck (pro sp.) [maxima 3 reticulata]
Orchard grass	*Dactylis glomerata* L.
Pacific yew	*Taxus brevifolia* Nutt.
Partridge pea	*Chamaecrista fasciculata* (Michx.) Greene
Pea	*Pisum sativum* L.
Peanut	*Arachis hypogaea* L.
Pearl millet	*Pennisetum glaucum* (L.) R. Br.
Pepper	*Capsicum annuum* L.
Perennial ryegrass	*Lolium perenne* L.
Petunia	*Petunia* spp. Juss.
Plantain	*Musa* spp. L.
Poison hemlock	*Conium maculatum* L.
Poison ivy	*Toxicodendron radicans* (L.) Kuntze
Poison oak	*Toxicodendron pubescens* P. Mill.

Common name	Scientific name
Ponderosa pine	*Pinus ponderosa* P. & C. Lawson
Potato	*Solanum tuberosum* L.
Prairie clover	*Dalea* spp.
Prairie dropseed	*Sporobolus heterolepis* (A. Gray) A. Gray
Prairie potentilla	*Potentilla arguta* Pursh
Prickly lettuce	*Lactuca serriola* L.
Prickly pear	*Opuntia* spp.
Proso (broomcorn millet)	*Panicum miliaceum* L.
Pumpkin	*Cucurbita pepo* L.
Purple foxglove	*Digitalis purpurea* L.
Purple loosestrife	*Lythrum salicaria* L.
Purple prairie clover	*Dalea purpurea* Vent.
Quack grass	*Elymus repens* (L.) Gould
Quinoa	*Chenopodium quinoa* Willd.
Ramie	*Boehmeria nivea* (L.) Gaudich
Raspberry, wild	*Rubus idaeus* L.
Red cedar	*Thuja plicata* Donn ex D. Don
Red clover	*Trifolium pratense* L.
Red pine	*Pinus resinosa* Ait.
Red top	*Agrostis gigantea* Roth
Redroot pigweed	*Amaranthus retroflexus* L.
Redstem	*Ammannia auriculata* Willd.
Reed canary grass	*Phalaris arundinacea* L.
Reed grass	*Calamagrostis* spp.
Rhubarb	*Rheum rhabarbarum* L.
Rice	*Oryza sativa* L.
Round-headed bush clover	*Lespedeza capitata* Michx.
Russian thistle	*Salsola kali* L.
Rutabaga	*Brassica napus* var. *napobrassica* L.
Rye	*Secale cereale* L.
Safflower	*Carthamus tinctorius* L.
Sagebrush	*Artemisia* spp.
Shepherd’s purse	*Capsella bursa-pastoris* (L.) Medik.
Shattercane	*Sorghum bicolor* (L.) Moench
Shooting star	*Dodecatheon* spp.
Showy ticktrefoil	*Desmodium canadense* (L.) DC.
Sideoats grama	*Bouteloua curtipendula* (Michx.) Torr.
Sisal hemp	*Agave sisalana* Perrine
Skyblue aster	*Aster azureus* Lindl.
Smooth sumac	*Rhus glabra* L.
Sorghum	*Sorghum bicolor* (L.) Moench ssp. *bicolor*
Soybean	*Glycine max* L.
Soybean (wild)	*Glycine ussuriensis* (L.) Merr.
Spelt	*Triticum aestivum* var. *spelta* L.
Spinach	*Spinacia oleracea* L.
Spotted knapweed	*Centaurea maculosa* Lam.
Squash	*Curcurbita* spp.
St. John’s wort	*Hypericum perforatum* L.
Stevia	*Stevia rebaudiana* (Bertoni) Bertoni
Stiff goldenrod	*Solidago rigida* L.

Common name	Scientific name
Stinging nettle	*Urtica dioica* L.
Strawberry	*Fragaria* spp.
Strychnine tree	*Strychnos nux-vomica* L.
Sudan grass	*Sorghum bicolor* (L.) Moench ssp. *drummondii* (Nees ex Steud.) de Wet & Harlan
Sugar beet	*Beta vulgaris* L.
Sugarcane	*Saccharum officinarum* L.
Sunflower	*Helianthus annuus* L.
Swamp milkweed	*Asclepias incarnata* L.
Sweet potato	*Ipomoea batatas* (L.) Lam.
Sweet sorghum	*Sorghum bicolor* (L.) Moench ssp. *bicolor*
Sweet clover	*Melilotus officinalis* (L.) Lam.
Switchgrass	*Panicum virgatum* L.
Tall blazing star	*Liatris aspera* Michx.
Tall fescue	*Schedonorus phoenix* (Scop.) Holub
Taro	*Colocasia esculenta* (L.) Schott
Tea	*Camellia sinensis* (L.) Kuntze
Teosinte	*Zea mexicana* (Schrad.) Kuntze
Timothy	*Phleum pratense* L.
Tobacco	*Nicotiana tabacum* L.
Tomato	*Solanum lycopersicum* L.
Trillium	*Trillium* spp. L.
Triticale	3 *Triticosecale rimpaui* Wittm.
Turnip	*Brassica rapa* var. *rapa* L.
Velvetleaf	*Abutilon theophrasti* Medik.
Water chestnut	*Eleocharis dulcis* (Burm. f.) Trin. ex Henschel
Water hemlock	*Cicuta maculata* L.
Water hyacinth	*Eichhornia crassipes* (Mart.) Solms
Watermelon	*Citrullus lanatus* (Thunb.) Matsumura & Nakai
Wheat	*Triticum aestivum* L.
White clover	*Trifolium repens* L.
White pine	*Pinus strobus* L.
White snakeroot	*Ageratina altissima* (L.) King & H. E. Robins.
Wild bergamot	*Monarda fistulosa* L.
Wild carrot	*Daucus carota* L. ssp. *carota*
Wild cherry	*Prunus serotina* Ehrh.
Wild chestnut	*Pachira insignis* (Sw.) Sw. ex Savigny
Wild garlic	*Allium vineale* L.
Wild licorice	*Glycyrrhiza lepidota* Pursh
Wild oat	*Avena fatua* L.
Wild plum	*Prunus americana* Marsh.
Wild rice	*Zizania aquatica* L.
Wild rye	*Leymus* spp. or *Elymus* spp.
Willows	*Salix* spp.
Witchweed	*Striga* spp.
Wood violet	*Viola* spp.
Wormwood	*Artemisia vulgaris* L.
Yam	*Dioscorea* spp.
Yarrow	*Achillea millefolium* L.
Yellow alfalfa	*Medicago falcata* L.
Yellow coneflower	*Ratibida pinnata* (Vent.) Barnhart

C. Scientific and Common Names of Insects

Source: Acquaah, G. (2002). *Principles of crop production: Theory, techniques, and technology* (2nd ed). Upper Saddle Rivde, NJ: Pearson Prentice-Hall.

Scientific name	Common name
Acrythosiphon pisum	Pea aphid
Anthonomus grandis	Cotton boll weevil
Aphis glycines	Soybean aphid
Aphthona flava	Flea beetle
Apis mellifera	Honeybee
Binodoxys communis	Soybean aphid parasitic wasp
Cactoblastis cactorum	Moth borer
Chrysoperla spp.	Green lacewing
Diabrotica spp.	Corn root worm
Empoasca fabae	Potato leaf hopper
Galerucella spp.	Leaf-eating beetles
Graminella nigrifrons	Black-faced leaf hopper
Heliothis zea	Corn ear worm
Hylobius transversovittatus	Weevil (root boring)
Hypera postica	Alfalfa weevil
Lepinotarsa decimilneata	Colorado potato beetle
Melanoplus spp.	Grasshoppers
Microstomus aethipoides	Stingless wasp
Nanophyes marmoratus	Weevil (flower feeding)
Oryzaephilus surinamensis	Saw-tooth grain beetle
Peregrinus maidis	Cornplant hopper
Popillia japonica	Japanese beetle
Pseudoletia unipuncta	Army worm
Pyrausta nubilalis	European corn borer
Sitophilus granaries	Granary weevil
Therioaphis maculata	Spotted alfalfa aphid
Trichoplusia ni	Cabbage looper moth

D. Scientific and Common Names of Crop Diseases

Source: Agrios, G. (1997). *Plant pathology* (4th ed.). New York, NY: Academic Press.

Scientific name of organism	**Disease caused**
Agrobacterium tumefaciens	Crown gall
Alternaria solani	Early blight of potato
Aspergillus spp.	Reduced grain quality
Cercospora zeae-maydis	Gray leaf spot of corn
Claviceps purpurea	Ergot
Cochliobolus sativus	Common root rot of small grains
Corynebacterium insidiosum	Bacterial wilt of alfalfa
Erysiphe graminis	Powdery mildew on cereals and grasses
Erysiphe polygoni	Powdery mildew on beans
Fusarium graminearum	Head blight of wheat
Fusarium oxysporum	Flax wilt
Gibberella spp.	Wheat and barley scab or head blight
Helminthosporium carbonum	Northern corn leaf spot
Heterodera glycines	Soybean-cyst nematodes
Melampsora lini	Flax rust
Meloidogyne spp.	Root knot nematodes
Monilinia fruiticola	Brown rot
Penicillium spp.	Reduced grain quality
Peronosclespora spp.	Downy mildew
Phoma macdonaldii	Phoma of sunflower
Phytophthora infestans	Late blight of potato
Pseudomonas syringae pv. *Phaseoli*	Halo blight
Puccinia graminis	Stem rust of wheat and other grains
Puccinia helianthi	Sunflower rust
Pyrenophora teres	Net blotch of barley
Pyrenophora tritici-repentis	Tan spot of wheat
Pyricularia grisea	Blast disease
Pythium spp.	Damping off
Rhizoctonia solani	Damping off
Sclerophthora spp.	Downy mildew
Septoria linicola	Pasmo of flax
Septoria tritici	Leaf blotch of wheat
Streptomyces scabies	Common scab of potato
Ustilago maydis	Corn smut
Ustilago nuda	Loose smut of small grains
Verticillium spp.	Verticillium wilt of numerous species
Xanthomonas campestris pv. *Malvacearum*	Angular leaf spot and bacterial blight
Xanthomonas phaseoli	Common blight



Appendix 2

Conversion Factors for Metric and Nonmetric Units

Source: American Society of Agronomy (2007). <https://www.agronomy.org/> Accessed 30 June 2010.

To convert Column 1 into Column 2, multiply by	Column 1 SI units	Column 2 non-SI units	To convert Column 2 into Column 1, multiply by
Length			
0.621	kilometer (km)	mile (mi)	1.609
1.094	meter (m)	yard (yd)	0.914
3.28	meter (m)	foot (ft)	0.304
3.94×10^{-2}	millimeter (mm)	inch (in)	25.4
2.47	hectare (ha)	acre (ac)	0.405
247	square kilometer (km^2)	acre (ac)	4.05×10^{-3}
0.386	square kilometer (km^2)	square mile (mi^2)	2.590
2.47×10^{-4}	square meter (m^2)	acre (ac)	4.05×10^{3}
10.76	square meter (m^2)	square foot (ft^2)	9.29×10^{-2}
1.55×10^{-3}	square millimeter (mm^2)	square inch (in^2)	645
Volume			
9.73×10^{-3}	cubic meter (m^3)	acre-inch (ac-in)	102.8
35.3	cubic meter (m^3)	cubic foot (ft^3)	2.83×10^{-2}
6.10×10^{4}	cubic meter (m^3)	cubic inch (in^3)	1.64×10^{-5}
1.057	liter (L)	quart (qt)	0.946
3.53×10^{-2}	liter (L)	cubic foot (ft^3)	28.3
0.265	liter (L)	gallon (gal)	3.78
33.78	liter (L)	ounce (oz)	2.96×10^{-2}
2.11	liter (L)	pint (pt)	0.473
Mass			
2.20×10^{-3}	gram (g)	pound (lb)	454
3.52×10^{-2}	gram (g)	ounce (oz)	28.4
2.205	kilogram (kg)	pound (lb)	0.454
1.10×10^{-3}	kilogram (kg)	ton (ton)	907
1.102	megagram (Mg)	ton (ton)	0.907
1.102	tonne (t)	ton (ton)	0.907

To convert Column 1 into Column 2, multiply by	Column 1 SI units	Column 2 non-SI units	To convert Column 2 into Column 1, multiply by
Yield and Rate			
0.893	kilogram per hectare (kg ha^{-1})	pound per acre (lb ac^{-1})	1.12
1.49×10^{-2}	kilogram per hectare (kg ha^{-1})	bushel per acre (bu ac^{-1}), 60 lb	67.19
1.59×10^{-2}	kilogram per hectare (kg ha^{-1})	bushel per acre (bu ac^{-1}), 56 lb	62.71
1.86×10^{-2}	kilogram per hectare (kg ha^{-1})	bushel per acre (bu ac^{-1}), 48 lb	53.75
0.107	liter per hectare (L ha^{-1})	gallon per acre (gal ac^{-1})	9.35
893	tonne per hectare (t ha^{-1})	pound per acre (lb ac^{-1})	1.12×10^{-3}
893	megagram per hectare (Mg ha^{-1})	pound per acre (lb ac^{-1})	1.12×10^{-3}
0.446	megagram per hectare (Mg ha^{-1})	ton per acre (ton ac^{-1})	2.24
Temperature			
(9/5 °C) + 32	Celsius (°C)	Fahrenheit (°F)	5/9 (°F −32)
Water Measurement			
9.73×10^{-3}	cubic meter (m^3)	acre-inch (ac-in)	102.8
9.81×10^{-3}	cubic meter per hour (m^3 h^{-1})	cubic foot per second (ft^3 s^{-1})	101.9
8.11	hectare meter (ha m)	acre-foot (ac-ft)	0.123
97.28	hectare meter (ha m)	acre-inch (ac-in)	1.03×10^{-2}
8.1×10^{-2}	hectare centimeter (ha cm)	acre-foot (ac-ft)	12.33
Concentrations			
0.1	gram per kilogram (g kg^{-1})	percent (%)	10
1	milligram per kilogram (mg kg^{-1})	parts per million (ppm)	1
Energy and Power			
9.52×10^{-4}	joule (J)	British thermal unit (Btu)	1.05×10^{3}
0.239	joule (J)	calorie (cal)	4.19
3.60×10^{6}	joule (J)	Kilowatt-hour (KW h)	2.78×10^{-7}
9.52×10^{18}	joule (J)	quad	1.05×10^{-19}
3.41	watt (W)	British thermal unit per hour (Btu h^{-1})	0.293
1.34×10^{-3}	watt (W)	horsepower (hp)	7.46×10^{2}



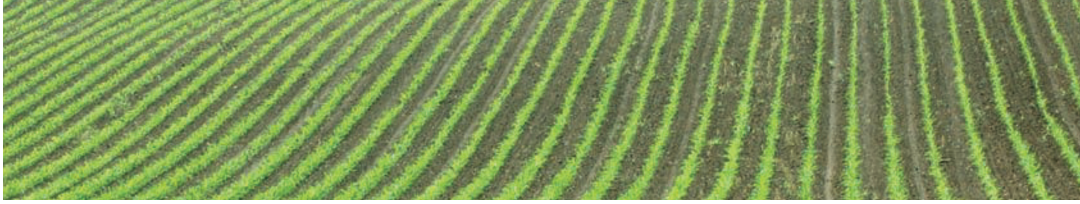
Appendix 3

Bushel Weight and Seeds per Pound for Various Crops

A bushel is a unit of volume that measures 2150 cubic inches (about 35,000 cubic centimeters). Seed has traditionally been sold in bushels, but today it is sold on a by-weight basis.
Source: Martin, J. H., and Leonard, W. H. (1967). *Principles of field crop production* (2nd ed.). New York: Macmillan Company.

Crop	Pounds/bushel	Kilograms/bushel	Seeds/pounds (in 1000s)
Alfalfa	60	27	220
Barley	48	21.6	13.5
Birdsfoot trefoil	60	27	1000
Buckwheat	48	21.6	15
Canola	50	22.5	140–210
Clover, crimson	60	27	150
Clover, ladino	60	27	860
Clover, red	60	27	260
Clover, white	60	27	700
Corn	56	25.2	1.5
Crownvetch	60	27	120
Field bean	60	27	1–3
Flax	56	25.2	82
Johnsongrass	28	12.6	130
Kentucky bluegrass	14	6.3	2200
Millet, foxtail	50	22.5	220
Millet, Japanese	35	15.8	155
Millet, pearl	45–55	20.4–25	85
Millet, proso	56	25.2	80
Oats	32	14.4	13
Orchard grass	14	6.3	590
Peanut	20–35	9–15.9	1
Redtop	14	6.3	5100
Reed canary grass	46	20.7	550
Rice	45	20.3	15
Rye	56	25.2	18
Smooth brome	14	6.3	137
Sorghum	56	25.2	14
Soybean	60	27	2.5
Sunflower, oilseed	24	10.8	6

Crop	Pounds/bushel	Kilograms/bushel	Seeds/pounds (in 1000s)
Sweet clover	60	27	250
Tall fescue	20	9	227
Timothy	45	20.3	1230
Vetch, common	60	27	7
Vetch, hairy	60	27	21
Wheat, durum	60	27	12
Wheat, winter	60	27	15
Wild rice	25	11.3	7.9

Glossary

Abiotic Environmental or nonliving components of an ecosystem.

Abiotic disease A plant disease or disorder caused by a nonliving factor, for example, air pollution.

Acre A land measurement with an area of 43,560 square feet; 4840 square yards; 4046 square meters.

Active ingredient The ingredient in an herbicide or pesticide that is the actual poison.

Adenosine triphosphate (ATP) A nucleotide used to transport chemical energy within cells for metabolism.

Adventitious root A root that arises from atypical areas on a plant such as nodes or stems.

Aerobic In the presence of oxygen.

Agrarianism A belief that promotes the idea that farming is a noble profession, the best way of life, and the most important economic endeavor.

Agribusiness The food and fiber section of the economy including all firms engaged in producing, processing, transporting, marketing, and distributing products that come from domesticated animals or plants.

Agricultural export Agricultural product that is sold and sent to other countries. Corn, soybean, and wheat are the largest U.S. agricultural exports.

Agricultural import Agricultural product that is brought from other countries. Grains, fruits, and vegetables are the largest U.S. agricultural imports.

Agriculture The process of cultivating land for the production of food, feed, fiber, and fuel from plants or animals.

Agrobacterium tumefaciens A pathogenic soil bacterium that is used to transfer genes when genetically modifying plants.

Agroecosystem An ecosystem that has been modified by inputs of fertilizers, pesticides, energy, and human labor to produce fiber, food, and shelter. Plants and animals selected for specific traits are components of agroecosystems.

Agroforestry A combination of agricultural and forestry practices that creates a diverse, productive, and sustainable land-use system.

Air masses Large bodies of air that have a similar temperature and moisture content.

Alfalfa A legume that is one of the oldest, cultivated forage crops for livestock feed. It is harvested as a hay or silage crop.

Alkaloid A natural, nitrogen-containing compound in some plants that is bitter tasting and can produce a physiological reaction in animals. Nicotine is an alkaloid found in tobacco.

Allele One form of a specific gene that controls a certain trait.

Allelopathic A plant containing compounds that inhibit some plants' growth.

Allelopathy The adverse effect of one plant on another due to the production of a chemical inhibitor.

Alley cropping An agroforestry system in which trees are grown in rows with annual or perennial herbaceous crops grown between the trees.

Alliance for a Green Revolution in Africa (AGRA) A partnership working to alleviate the poverty and hunger of millions of small-scale farmers across Africa.

Alluvial soil Rich, fertile soil that was originally deposited by rivers or moving water.

Amaranth An annual broadleaf crop grown for grain or forage.

Amino acid Molecules with a common structure consisting of a central carbon (C) with hydrogen (H), an amino group (NH_2), and a carboxyl group (COOH). Twenty different amino acids are used in protein synthesis.

Amino acid synthesis inhibitor A type of active ingredient in some herbicides. It disables the enzymes responsible for the synthesis of specific amino acids.

Anatomy The study of the arrangement of cells, tissues, organs, and other structures of an organism.

Anhydrous ammonia A common form of synthetic nitrogen fertilizer that is injected into the soil from a pressurized cylinder.

Animal and Plant Health Inspection Service of the USDA (APHIS) This organization prevents the introduction of parasitic plant pests and noxious weeds into the United States.

Annual plant A plant that completes its life cycle in one year or growing season. Winter and spring annuals are two types.

Antiquality factor The components of forage or feed quality that reduce palatability or animal performance; includes factors such as chemical toxins or morphological features.

Apical meristem Actively dividing cells found at the tip of a plant root or shoot.

Aquatic plants Plants that grow in water.

Arable land Land that is suitable to be used as cropland. This includes all presently cultivated land as well as land that has potential for agriculture.

Arid region An area of the world that receives less than 10 inches (25 centimeters) of rain annually.

Asexual reproduction Reproduction of plants through vegetative means such as rhizomes and stolons. Asexual reproduction does not involve exchange of genetic materials.

Atmosphere The gaseous layer that surrounds the earth and extends 70 miles (113 kilometers) into space. Important atmospheric gases are nitrogen, oxygen, water vapor, and carbon dioxide.

Atmospheric fixation The process in which energy from lightning converts atmospheric nitrogen to nitrate that falls to the soil with rain or snow and is available for plants to use.

Atom The smallest component of an element that has all of the chemical and physical properties of the element; consists of a nucleus made of protons and neutrons with electrons circling the nucleus.

Atomic number A number assigned to elements based on their number of protons.

Auricle An appendage on the collar of a grass plant.

Axillary meristems A group of actively dividing cells found at the side nodes of a plant; also called axillary buds. They are responsible for the development of branch or flower buds.

Bacteria Microscopic (1 to 3 micrometers), single-celled organisms that reproduce by fission.

Barley A small grain crop that is one of the oldest cultivated crops. It is most commonly known for its use for making malt for fermentation in beer production. It is also made into breads, porridges, and soups.

Bermuda grass An introduced, warm-season, perennial grass adapted to tropical locations and used for forage in the South.

Berseem clover An annual clover used as a forage.

Biennial plant A plant that completes its life cycle in two years or growing seasons.

Big bluestem A native, perennial, warm-season grass used for forage and prairie restoration.

Binder A machine that ties bundles (sheaves) of grain and deposits them in the field.

Biodiesel A renewable, nonpetroleum fuel that is produced from chemical processing of vegetable oil; typically the oil extracted from soybeans or canola.

Biodiversity Refers to the variety of plants and animals in a given area. High biodiversity is characteristic of natural ecosystems and is important because of the ways in which different plants and animals interact with one another.

Bioenergy Renewable energy extracted from plant biomass or animal waste that contains energy originally derived from the sun. Bioenergy crops include grains such as corn, crop residue such as corn stover, woody biomass such as willow and timber wastes, and herbaceous crops such as switchgrass and prairie plants.

Biofuel crop Plant material used as a fuel source. Some examples are corn for production of ethanol, hybrid willow or switchgrass for combustible pellets, grasses or legumes for conversion to biogas.

Biological magnification An increase in the concentration of a substance as it moves up a food chain.

Biological pest management A pest management method that uses a living organism to control a pest problem by predation, parasitism, or competition.

Biological weed control The use of biological organisms or agents such as diseases, insects, or animals to reduce or eliminate pests.

Biomass crop A crop that is grown and harvested for the production of energy by fermentation, combustion, or gasification.

Biome A large-scale, natural, terrestrial ecosystem containing specific communities of plants and animals.

Biosphere The entire collection of all living things on the earth in both land and water ecosystems, ranging from a few meters below the surface to a few meters above the surface.

Biotechnology The scientific techniques used to genetically manipulate living organisms to produce useful products.

Biotic The biological or living components of an ecosystem.

Biotic disease A plant disease caused by living organisms such as fungi, bacteria, viruses, and nematodes.

Biotype A population of organisms that share a similar and distinctive genotype.

Birdsfoot trefoil A legume crop that is adapted to temperate regions and used for pastures or hay.

Black layer The layer in corn and sorghum seeds that restricts translocation of carbohydrates to the seed. Its formation indicates physiological maturity of the crop.

Blade The flat surface of a plant leaf that is exposed for maximum interception of sunlight for photosynthesis. A simple leaf of a dicot has only a blade and a petiole that attaches it to the stem. A grass leaf has three components: blade, sheath, and collar.

Bloat A sickness in ruminants such as cows and sheep that occurs when they graze on certain legumes. Because of the high soluble carbohydrate and protein levels, gases are trapped in the rumen forming a froth, causing the rumen to swell. Animals may die of suffocation and internal hemorrhaging.

Body mass index (BMI) An index for determining ideal body size based on age, weight, and height.

Broadcast cultivation Field cultivation performed after the crop is planted without regard to crop rows; also called *blind cultivation*.

Broadcasting A seeding approach in which the seeds are randomly, yet evenly, spread over the top of the seedbed in a field; also called broadcast seeding

Broadleaf A general term applying to dicot plants, which typically have broad leaves with netted venation.

Buckwheat An annual, dicot seed crop that can be used for human and animal feed. It is not genetically related to wheat.

Bulb A swollen underground stem surrounded by concentric, fleshy rings that are modified leaves.

Bushel A unit of volume for expressing crop yield. A bushel is the amount that can be held in an 18.5-inch (47-centimeter) diameter by 8-inch (20-centimeter) deep container. Its volume is 2150 cubic inches (about 35,000 cubic centimeters). Today, grains are traded based on a standard weight per bushel.

C_3 plants Plants that use a type of carbon fixation common in temperate plants. C_3 plants use the Calvin cycle and are called C_3 plants because the first molecule formed has three carbons (phosphoglyceric acid). Examples of these plants include wheat, alfalfa, and Kentucky bluegrass.

C_4 plants Plants that use a type of carbon fixation in which the first stable compound formed is a four-carbon molecule (oxaloacetic acid). Examples include crops of tropical origin such as corn, sorghum, and sugarcane.

Calorie A measurement of energy content of a food or plant material. It is the amount of energy required to increase the temperature of 1 gram of water by 1 degree Celsius.

Calvin cycle The second part of photosynthesis (carbon-fixation reactions) in which carbon dioxide is turned into simple sugars.

Cane The long, flexible stem of certain plants including sugarcane, bamboo, or raspberry.

Canola A crop that produces polyunsaturated oil that is used for cooking; the same species as rape, but bred to lack the inedible erucic acid found in rape.

Capillary water Water that is held in small pores within a soil and is an important source of water for plants.

Capsaicin The compound found in chili peppers that is responsible for the heat of chili peppers.

Carbohydrates Energy-rich organic compounds that are composed of carbon, hydrogen, and oxygen. These include sugars, starches, and cellulose.

Carbon cycle The movement of carbon through the different reservoirs of the earth's ecosystem.

Carbon dioxide (CO_2) A gas formed from bonding a carbon and two oxygen molecules. Carbon dioxide is the raw material for photosynthesis and plays a large role in the greenhouse effect.

Carbon fixation The conversion of carbon dioxide into organic compounds by plants through the process of photosynthesis.

Carbon-fixation reactions The second part of photosynthesis, in which carbon dioxide is turned into organic compounds.

Carbon:nitrogen ratio (C:N ratio) The relative content of carbon and nitrogen that influences the rate of decomposition.

Carbon sequestration The process of removing carbon from the atmosphere for storage in carbon reservoirs such as in plant tissues, the soil, or in the ocean.

Carbon trading A market-based approach to encourage the reduction of the amount of CO_2 entering the atmosphere.

Cassava A tropical crop that produces large roots that are 30 percent starch and are used to make a number of different foods depending on the local culture.

Cation exchange capacity (CEC) The CEC is the amount of exchangeable cations (positively charged ions such as H^+, Al^+, and Ca^+) a soil can sustain. A soil with a high cation exchange capacity holds many nutrients and is usually fertile.

Celiac disease A hereditary intolerance for gluten, a protein in cereals such as wheat.

Cell membrane disruptor Herbicides that kill plants by rupturing the cell membrane.

Cellulose A long-chained, glucose polymer important to the structural support of plants. Cellulose is often linked to lignin and hemicellulose in plant cell walls.

Cereal crop A grass that produces edible grain.

Chemical fallow The use of herbicides to keep volunteer weeds from growing in an area not planted with a crop.

Chemical pest management A pest management method that uses chemical pesticides as a way to control or suppress a plant pest.

Chickpea A legume that is grown for its edible seed, which is used in salads and soups. It is a cool-season annual.

Chilling injury Damage to plants caused by the disruption of cell membrane integrity due to exposure to cold temperature.

Chisel plow A tillage implement consisting of a small blade attached to a shank. It does not turn the soil over, and it provides minimal incorporation of crop residues.

Chlorophyll Green pigment within chloroplasts that absorbs photons of light energy used in the process of photosynthesis.

Chloroplast Organelle located in mesophyll cells within leaves. It is where photosynthesis occurs.

Cholesterol A steroid lipid in animals that is essential for membrane, hormone, brain, and nervous tissue formation.

Chromosome A structure that is composed of DNA and contains genes found in cell nuclei. Each chromosome contains hundreds to thousands of genes.

Climate The typical, long-term weather conditions in a region.

Clone-former A plant where the original parent plant is replaced by new plants that are established vegetatively by rhizomes, stolons, or adventitious roots.

Clovers A group of forage legumes grown on considerable acreage. There are both perennial and annual species including red clover, white clover, berseem clover, kura clover, and crimson clover.

Coca A shrubby perennial grown as a psychoactive crop to produce cocaine.

Collar An area of a grass leaf that joins the blade and the sheath. Collars can contain appendages such as auricles and ligules.

Collenchyma A type of tissue where plant cells are closely compacted and provide structural support to the plant.

Columbian Exchange The trade of crops, livestock, diseases, and people that occurred between the New World and Old World after Columbus's voyage to the New World.

Combine Machinery used to harvest grain crops; called a *combine* because it combines cutting, binding, and threshing of the grain into one machine.

Commodity payment Government financial support paid to farmers to ensure production of important crops and to maintain low food prices.

Companion crop A crop that is used to help establish small-seeded forage crops by providing ground cover and weed control for the slower growing forages.

Competition In plants, the process in which crops and weeds vie for growth factors such as nutrients and sunlight.

Complete flower A flower that has all four flower parts: stamens, pistil, petals, and sepals.

Compound leaf A leaf that has a blade composed of two or more leaflets attached to the petiole. Compound leaves may have a palmate or pinnate arrangement.

Confinement feeding When animals are kept and fed in confined areas. This enables farmers to cut costs and create a more standardized product.

Conservation payment Government financial support used for programs aimed at reducing crop production on environmentally sensitive land.

Conservation planting The plantings of native, perennial grasses or other designated woody species for the purpose of conserving the soil from wind or water erosion.

Conservation Reserve Program (CRP) A program that rents environmentally sensitive land from landowners, who retire that land from agricultural production.

Conservation tillage A tillage approach in which 30 percent or more of the crop residue is left on the soil surface to reduce erosion.

Consultative Group on International Agricultural Research (CGIAR) A partnership of countries, private foundations, and international organizations that funds and directs international research institutes.

Consumer Organisms that consume producers (other organisms).

Contact herbicide An herbicide that kills vegetation by destroying cells when it is applied to the leaves, flowers, and stems of plants. Perennial plants with established root systems may not be killed by this type of herbicide.

Continuous cropping Growing the same crop on the same land for two or more years.

Continuous grazing A system in which animals have uncontrolled access to a large pasture where they are free to move around and choose the most palatable plants.

Contour strip cropping A soil- and water-conservation method in which annual crops are grown in alternating strips with perennial crops, and these strips follow the contours of the land rather than a straight line.

Conventional agriculture An industrialized agricultural system in which mechanization, monocultures, and chemical fertilizers and pesticides are used. The minimization of production cost is critical. It is also known as *industrialized agriculture*.

Cool-season grasses Grasses that have optimum growth around 75°F (24°C). Their growth is reduced when temperatures reach or exceed 90°F (32°C).

Cork cambium A type of secondary meristem found in woody plants.

Corm An underground stem that is compressed and solid, with outer appearance similar to a small bulb. Timothy is a perennial grass that stores energy in corms at the bases of stems.

Corn A tall-growing, annual grass of tropical origin that is grown and harvested for its grain. Corn is the most economically important crop grown in the United States.

Corn Belt An area of the midwestern United States that has historically produced much of the U.S. corn crop. This area includes portions of Iowa, Illinois, Minnesota, Wisconsin, Michigan, Indiana, and Ohio.

Corn silage Silage that is made from whole corn plants, chopped into small pieces.

Cotton A tropical crop grown as an annual in the southern United States to produce fiber.

Cover crop A crop planted to protect the soil between harvest of a cash crop and planting of the next cash crop.

Cover cropping A type of multiple-cropping system in which a cover crop is grown following harvest of the cash crop.

Cowpea A grain legume used as human food.

Crassulacean acid metabolism (CAM) plants Plants with a type of photosynthesis in which carbon dioxide fixation occurs at night. This enables plants to survive very hot, dry conditions. Examples include cacti and pineapple.

Crimson clover An annual, forage legume.

Crop Equivalency Rating (CER) A system for categorizing soils based on profitability of soils for crop production. This system is being phased out in favor of the Crop Productivity Index system.

Crop insurance Insurance purchased by farmers to protect losses from natural causes or from revenue loss.

Crop Productivity Index (CPI) A system for categorizing soils based on their capacity for crop production.

Crop residue Plant material that is left on the soil after harvesting.

Crop rotation A planned sequence of different crops that are grown over the years on the same land.

Cropping system The management of crops in space and time to efficiently use the available climatic and soil resources.

Cross-pollination Pollination that occurs when the pollen of one plant fertilizes the ovule of another plant.

Crown-former A plant, often with a deep taproot, that does not spread vegetatively and relies on seeds for reproduction.

Cultivar A group of genetically similar plants of a crop species that can be distinguished from other groups of plants in the same species. Cultivars are a product of human selection, and are developed to have specific, desirable characteristics.

Cultivating tillage Tillage for weed control that is performed after the crop is planted.

Cultural pest management A management method that attempts to control a pest problem by manipulating the environment in which a plant or crop is growing.

Cultural weed control Weed control methods that include rotation, cover crops, smother crops, mulches, or delayed planting as opposed to mechanical weed control operations.

Day-neutral plant A plant that flowers with any duration of day length.

Dead zone A zone in the ocean where hypoxia occurs because excess growth of plankton and algae and subsequent decomposition consumes all of the oxygen. A dead zone occurs where the Mississippi River meets the Gulf of Mexico.

Denitrification The process of nitrate being converted to N_2 under anaerobic conditions by soil bacteria.

Dent corn The most widely grown type of corn today. It originated from the crossing of flour and flint corns.

Deoxyribonucleic acid (DNA) A nucleic acid that contains the genetic information to regulate the development and functioning of living organisms; the main component of chromosomes.

Deserts Regions where annual rainfall is between 5–10 inches (13–25 centimeters), and daytime temperatures are high.

Determinate Plants that cease additional vegetative when flowering starts.

Developed countries Countries that have a high national income per capita (average = $30,000) and a higher Human Development Index.

Developing countries Countries that have a low national income per capita (average = $450) and a lower Human Development Index.

Development In plants, the process of growth and differentiation that includes several stages.

Dicot A plant whose embryo has two seed leaves (cotyledons).

Dicoumarol A chemical that reduces the blood-clotting ability of animals. Consumption of it can result in death from internal or external bleeding.

Dietary reference intakes (DRI) Food-consumption standards developed by the U.S. government that promote healthy, nutritional diets.

Dioecious plants Plant species that have separate male and female plants. For pollination to occur, both kinds of plants must be present. An example is hops.

Direct cut silage Silage that is cut and chopped from the field in the same day.

Disaccharide A compound of two monosaccharides. Examples include sucrose (glucose and fructose) and maltose (glucose and glucose).

Disaster payment Government financial support paid to farmers when a natural disaster like drought or a severe storm occurs and damages crops, livestock, and buildings.

Disease triangle The three necessary components for a plant disease to occur: a pathogen, a susceptible host, and a favorable environment.

Disk A common tillage implement that has large, concave plates with a sharp edge to slice and mix the soil in a field.

Distillers grains A by-product of corn ethanol production or beer production; usually used for livestock feed.

Diurnal Daily variation; for example, the heating and cooling of a place on the earth due to variation in the sunlight reaching that place in the daytime and the nighttime.

Diversity See *biodiversity.*

Domestication Adapting or manipulating wild plants and animals to use for food production.

Dormancy Occurs when plants enter a resting stage in response to environmental stimuli. In northern latitudes, many perennial plants undergo a dormancy reaction in response to shorter days in the fall.

Double crop A multiple cropping strategy in which two crops are grown during a single growing season.

Drainage system A system used to remove excess water from soil so that it does not interfere with agricultural operations and plant growth. There are two main types: surface and subsurface.

Drilling A seed planting approach that deposits the seeds in a row at a uniform depth in the seedbed.

Drought A prolonged period of below normal precipitation that results in damage to crops and reduced yield.

Dry climate Climate that lacks adequate precipitation for the growth of many plants.

Dry matter The dry weight of plants that excludes moisture. This is the most commonly used measure of growth.

Dust Bowl A period in the 1930s when extreme drought and tillage caused the loss of topsoil in the southern plain regions of the United States, leading to economic devastation.

Ear The female part of a corn plant that at maturity contains the corn grain on a cob.

Ecological footprint The combined environmental resources required to support the human population and absorb its waste.

Ecological pyramid The energy or resource amounts at different steps or levels of a food chain. Because loss of energy or other resources occurs within a food chain, the amounts are less at each step.

Ecological succession The process of gradual change or replacement of communities of plants over time.

Ecology The science of the mutual relationships among biological organisms and their interaction with the environment.

Ecosystem The community of organisms and their environment, and how they interact.

El Niño A condition in which the normal, east–west circulation in the Pacific Ocean is altered, and warmer ocean water is moved to the Pacific coast of South America and California. This causes warmer and drier winters for the northern third of the United States and very wet conditions in the southern states.

Electron One of the three subatomic particles in an atom. Electrons have a negative charge and orbit around the nucleus of the atom.

Element Building blocks of all living and nonliving things; composed of only one kind of atom. More than 100 elements have been identified. Examples include hydrogen, nitrogen, carbon, and calcium.

Elevation The height above the average sea level. As elevation changes, the air temperature changes.

Energy The physical capacity of a system to do work.

Enriched Refined flour products that have had nutrients added to replace those lost during processing.

Ensiling The process of making silage.

Environmental Protection Agency (EPA) A government agency that is in charge of protecting human health and the natural environment.

Epidermis The outer, protective layer of cells found on all primary plant parts.

Epigeal A type of seedling emergence in which the hypocotyl lengthens and carries the cotyledons above the soil surface.

Equator An imaginary line around the earth. It is equidistant from the North and South Poles. This divides the earth into the northern and southern hemispheres.

Erosion The detachment and movement of soil minerals and organic matter by wind and water.

Essential element An element that is necessary for a plant to complete its growth cycle whose functions cannot be replaced by other elements. Essential elements are components of compounds such as enzymes.

Evaporation The transition of water from the liquid to gaseous state on the surface of leaves or the soil. The sun provides the energy that drives most evaporation on the planet.

Evapotranspiration (ET) The total water loss from an area of land due to evaporation from soil and plant surfaces and transpiration by plants.

Evenness The distribution or relative abundance of the individuals of a species.

Extension education service This service was established to transfer research information from universities and experiment stations to farmers, and to educate farmers about best practices.

Eyes Dormant buds that are contained in tubers.

Faba bean A warm-season grain legume.

Fall equinox One of only two times a year when equal amounts of solar radiation reach both the northern and southern hemispheres. Fall equinox in one hemisphere is the same time as spring equinox in the other hemisphere. The hemisphere experiencing fall equinox will proceed to lessening solar radiation and shorter daylight hours until winter solstice.

Fallowing A strategy used in semiarid regions for accumulating moisture in the soil. A crop is not grown, and weeds are controlled using tillage or herbicides.

Farm A plot of land devoted to agriculture and the raising of crops and domesticated animals. A place where humans live and practice stewardship of the land and nature.

Farm bill Government legislation involving agriculture and food supply.

Fat Simple lipid derived from animals. Fats are solid at room temperature.

Federal seed laws Laws established to provide growers and other consumers essential information about seed they purchase. This information is found on the label of the purchased seed.

Feekes scale A numerical scale used to assign developmental stages in grasses. The scale ranges from one (the first-leaf stage) to eleven (the grain-ripening stage).

Fertile Crescent An area from the eastern coast of the Mediterranean Sea to the Persian Gulf. Many plants and animals were first domesticated here.

Fertilizer An organic or inorganic material applied to the soil to promote plant growth. A fertilizer may contain a specific nutrient or may be used to increase the availability of other plant nutrients.

Fiber It is associated with the structural parts of plants. *Fiber* can refer to a substance that is consumed in the diet from plants and that is not broken down

in the digestive tract. It can also mean a plant-derived substance used to make textiles, rope, paper, and baskets.

Fiber crop A crop that produces fiber that can be extracted and used to make durable products. Examples include cotton and sisal.

Fibrous root system A root system that is made up of several primary roots that branch and develop many lateral roots to form an interwoven mass.

Field bean Bean that is harvested for the mature dry seeds, not the edible pods. These include navy and kidney beans. They are consumed mostly by humans but can also be used as livestock feed.

Field capacity The soil water content held in pore spaces after drainage of gravitational water. The water is readily available to plants.

Field pea A grain legume used for human food or livestock feed.

Flame weeding A mechanical weed control operation that uses propane fuel to kill weeds by burning them.

Flax One of the oldest crops grown for fiber and for seed. Flax is grown today as a source of omega-3 fatty acids for human nutrition.

Flint corn Corn that has a small, starchy endosperm enclosed in a thick, hard endosperm. Flint corns were likely the first types domesticated by Native Americans.

Flooding Water overflowing rivers, streams, and ponds because of excess precipitation or a high rate of snowmelt. This can cause significant crop loss.

Flour corn Corn that has soft starch throughout the kernel and was widely used by native cultures for grinding into flour or meal. Currently, it is used for the production of tortillas and corn chip food products.

Flowers Modified leaves that contain the sexual reproductive organs of a plant. Complete flowers have petals, pistils, stamens, and sepals.

Food chain The progressive flow of energy and nutrients in an ecosystem from producers through consumers.

Food Guide Pyramid A simple visual aid designed by the USDA to provide guidance to humans on proper food consumption to meet their nutritional needs.

Forage The vegetative portions of plants used for livestock feed.

Forage quality The potential forage feeding value of a crop. Features of forage quality are nutrient concentration, palatability, and antiquality components.

Forage radish A brassica species used as a forage or cover crop.

Forests The most productive terrestrial biome consisting of a dense growth of trees and underbrush.

Fossil fuels Nonrenewable fuels such as oil, coal, and natural gas that come from the ancient remains of plant, animal, and microbe growth.

Freezing injury Occurs when ice forms in cells and damages both the cell membrane and cell organelles.

Fructose The sweetest simple sugar. Has the same chemical makeup as glucose but a different structure. Found naturally in fruits and honey.

Fruit A mature or ripened portion of a plant (often the ovary) containing a seed or seeds; may be fleshy or dried.

Fungi Biotic organisms composed of filamentous threads called *hyphae* that absorb nutrients for survival. Fungi may be parasites or saprophytes on plants.

Gametes Cells produced after meiosis. They contain half of the original genetic material.

Gene A sequence of nucleotides found in chromosomes. Genes control the inheritance of traits and an organism's development.

General use pesticide A pesticide that presents little danger to humans or the environment when applied according to the directions. Typically, no license is required to apply general use pesticides.

Genetic engineering The use of biotechnology to produce desirable traits by altering a plant's DNA.

Genetic pest management A pest management method that uses plant breeding and genetic engineering to develop plants that are more resistant to significant plant pests.

Genetically engineered organisms (GEOs) Organisms that have had a desirable trait added to them through the process of genetic engineering.

Genetically modified organisms (GMOs) Organisms that have had a desirable trait added to them through the process of genetic engineering.

Genotype The entire genetic component of an organism.

Genus A group of related species. Also the first part of the scientific name of plants and animals.

Germination The onset of growth of a new plant from a dormant state within a seed. Caused by favorable water, temperature, and light conditions.

Global warming An increase in the average global temperature over the past 100 years due to enhancement of the greenhouse effect caused by increasing concentrations of atmospheric gases.

Glucose The most abundant simple sugar, a six-carbon monosaccharide. The first product of photosynthesis that is metabolized and used for formation of complex carbohydrates.

Gluten A protein that is found in certain small grains.

Glycogen A long-branched, chain polymer of glucose. The only carbohydrate that occurs in animals.

Glyphosate The common name for a nonselective, contact herbicide. The most widely used herbicide.

Grain crop A crop in which the grain is harvested. Examples are corn, soybean, and wheat.

Grain drill A type of drill used to plant seed, generally small grains, in narrow rows that are often only 6 inches (15 centimeters) apart.

Grasslands Regions where grasses dominate the vegetation growing in the region.

Gravitational water Water that drains through the soil and is not held in the soil pores.

Grazing land Agricultural land with vegetation suitable for grazing livestock.

Green manure crops Fast-growing crop plants that are incorporated into the soil while still vegetative, with the intent of improving nutrients and soil quality.

Green Revolution The use of high-yielding crops combined with the use of fertilizers and pesticides to increase global food production, especially in tropical regions.

Greenhouse effect A natural process in which the atmosphere absorbs solar radiation reflected off of the earth's surface. The main greenhouse gases are water vapor, carbon dioxide, methane, and nitrous oxide.

Gross domestic product (GDP) The measure of the value of a nation's total production of goods and services.

Ground tissue A primary plant tissue—other than the epidermis or conducting tissue—whose function is to provide a plant with storage and support.

Growing Degree Day (GDD) A unit of measurement of heat accumulation for plants.

Growth Increase in weight or size of an organism because of an increase in the number and size of cells.

Growth regulator A selective herbicide that disrupts plant growth by interfering with hormones and protein synthesis.

Habitat The particular place providing the resources for a plant or animal to live.

Harrow A secondary tillage implement used to smooth and level the soil surface and reduce soil particle size.

Harvest The manual or mechanical removal of a crop's grain or biomass from the field. For grain, this occurs at the completion of the crop production cycle.

Harvest maturity The moisture content of the crop when a combine can harvest the grain with minimal field loss.

Hay Forage that has been dried in the field to 15–20 percent moisture concentration and stored in aerobic conditions.

Hay crop silage Silage made from alfalfa and other grasses. It is lower in energy but higher in fiber and protein content than corn silage.

Haylage Hay crop silage that is dried to a moisture content of about 50 percent. See *wilted silage.*

Heat injury Injury to plants caused by overly high temperatures that interfere with the plant's metabolic processes.

Hemp A tall-growing annual, native to Asia. It is one of the oldest fiber crops used for textiles, paper, and construction.

Herbicide A chemical agent used to kill plants. It is the most common form of weed control.

Herbicide resistance Occurs when weed species that were once susceptible to herbicides develop an ability to survive treatment with the herbicide.

Herbicide tolerance An ability to withstand treatment from an herbicide that is specifically selected for or genetically engineered into a crop.

Heritability The proportion of a phenotype that is controlled by genes.

Heterosis Also known as *hybrid vigor*. The phenomenon in which the F_1 offspring of two inbred parents has a superior phenotype due to increased heterozygosity in its genotype.

Heterozygous An organism that contains different alleles for a given trait.

High density lipoprotein (HDL) Complex associations of cholesterol, lipids, and protein that transport and deposit cholesterol. HDL is considered good cholesterol because it helps remove other forms of cholesterol from the blood.

High fructose corn syrup A widely used, inexpensive sweetener formed by processing corn grain; a blend of fructose and glucose. It has a higher proportion of fructose than normal corn syrup, and is the main sweetener used in soft drinks, fruit juices, candies, and processed foods.

Hobby farm A farm characterized as being highly dependent on off-farm income. Hobby farms average 100 acres (41 hectares) or less and earn less than $10,000 annually in farm sales.

Homestead Act of 1862 This act provided a U.S. citizen, 21 years or older, the right to claim 160 acres (65 hectares) of public land with the provision that the homesteader had to live on the land for 5 years and make improvements.

Homozygous An organism that has only one type of allele for a given gene.

Horizon A distinct layer of a soil profile formed due to weathering, leaching, humus formation, or other processes.

Host A plant infected by a pathogen or parasite.

Hot spot A circular, localized area of diseased plants in a field due to a nematode infection; an important diagnostic indication of nematode diseases.

Humid region An area of the world with more than 40 inches (102 centimeters) of precipitation in a year.

Humus A complex part of soil organic matter consisting of waxes, lignin, and carbon fractions that are resistant to decay.

Hunting and gathering An early human lifestyle in which the daily search for food by hunting and gathering of animals, seeds, and roots was a preoccupation and necessity for survival.

Husking or shucking The process of removing the leaf-like covering from an ear of corn.

Hybrid In crop breeding, the offspring of a cross between two distinct types of one crop species. Also, the offspring that result when two organisms from different species reproduce.

Hybrid corn Corn resulting from the crossing of two inbreds. Hybrid corn seed is sold by commercial seed companies and is the primary type grown by producers today.

Hybrid vigor Also known as *heterosis*. The phenomenon in which the F_1 offspring of two inbred parents has a superior phenotype due to increased heterozygosity in its genotype.

Hybridization The crossing of two parent plants of differing genotypes to produce a hybrid.

Hydrophyte A plant that grows in water and has the ability to extract oxygen from water, for example, wild and cultivated rice.

Hypogeal A type of seedling emergence in which the cotyledons remain beneath the soil surface and the epicotyl emerges from the soil.

Hypoxia A condition of reduced concentrations of dissolved oxygen in water; caused by high nutrient levels that lead to excess growth of microorganisms. See *Dead zone*.

Immobilization The process of converting inorganic nitrogen to organic nitrogen by soil microbes.

Imperfect flower An incomplete flower that lacks either the stamen (male) or the pistil (female) components. An example is corn.

Inbred Plants that are repeatedly self-pollinated to create a uniform variety. Inbred plants are later crossed to produce hybrids.

Incomplete flower A flower that lacks one or more of the four flower parts: stamens, pistils, petals, or sepals.

Indeterminate Plants that have continual stem elongation and vegetative growth after flowering and throughout the growing season.

Industrial fixation The process of taking ionic nitrogen (N_2) from the air and converting it to nitrogen-bearing compounds to be used as fertilizers, such as anhydrous ammonia, urea, or ammonium nitrate.

Industrialization of agriculture Modern farms are considered to be industrial factories producing raw materials for the food industry. The minimization of production cost is critical. It is also known as *conventional agriculture*.

Inert ingredient Ingredients that are added to herbicides to aid in the handling and application process and to increase the activity of the herbicide.

Inflorescence A flower arrangement composed of a cluster of individual flowers or florets.

Inorganic fertilizer A fertilizer that is synthetic or mined; may supply either a macro- or micro-element. Examples are urea, a nitrogen source; and potash, a potassium source.

Intake The amount of food a livestock animal will consume.

Integrated pest management (IPM) A strategy that incorporates five management methods (cultural, biological, mechanical, genetic, and chemical) to control plant pests. It examines all possible methods and determines which are economically feasible and environmentally sound for the pest problem involved.

Intercalary meristem Actively dividing cells that are independent of the apical meristem and are responsible for the growth of the internodes and leaves of grasses.

Intercropping The system of growing two or more crops on the same piece of land at the same time. It is also called *polyculture*.

International research institutes Region-specific institutes that work to help improve locally important crops and their production. These were vital components of the original development of the Green Revolution.

Internode The portion of the stem between the nodes.

Interrow cultivation Mechanical weed control operation where cultivation occurs between crop rows.

Inulin A unique polysaccharide of fructose. The primary storage carbohydrate in the roots and tubers of the composite family, such as Jerusalem artichoke and dandelion.

IPAT equation An equation used to look at the environmental impact of resources used and wastes generated by a human population.

Irrigation The process of applying water to meet plant needs. Irrigation is typically applied with sprinkler or flood systems, but "drip irrigation" is used for some high-value fruit and vegetable crops.

Jerusalem artichoke A member of the sunflower family used as a starch crop. It stores energy in tubers as inulin. It was used by Native Americans and colonists as an energy source but has a very small market in the United States today.

Koppen system A system developed by Wladimir Koppen, a German climatologist, dividing the earth into climate regions based on temperature and precipitation. This system also identifies five major climate types along with subclimates.

Kura clover A perennial forage legume adapted to northern regions.

Lactose A disaccharide from glucose and galactose that is found in human and cows' milk. It is less sweet than sucrose and supplies about 50 percent of the energy found in cows' milk.

Latitude A measurement in degrees of north or south position on the earth. Ranges from 0° at the equator to 90° at the poles. Latitude and longitude systems were originally developed to aid in navigation and mapping of locations on the earth.

LC_{50} A measurement used to determine the toxicity of herbicides and pesticides. LC_{50} is in milligrams per kilogram of body weight in air or water that will kill 50 percent of the test population.

LD_{50} A measurement used to determine the toxicity of herbicides and pesticides. LD_{50} represents a single dose in milligrams of substance per kilogram of body weight that will kill 50 percent of a particular test population.

Leaves Primary organs in plants. Responsible for the essential processes of light interception, photosynthesis, and transpiration.

Legumes Any plant belonging to the family Fabaceae; most notably known for their ability to fix atmospheric nitrogen into the soil. Examples are alfalfa, clovers, and beans.

Lentil A cool-season, annual legume native to the region east of the Mediterranean Sea. It produces high-protein seeds used mostly for human food.

Life-cycle analysis A method used to analyze energy inputs and outputs at all stages of production. This provides information that can help determine which options are the most sustainable.

Light intensity Refers to the brightness of light and is affected by time of day, latitude, season, and topography of the land.

Light quality Described in terms of wavelength of sunlight. Plants are adapted to a specific light quality, which they use for photosynthesis.

Light reaction The first part of photosynthesis in which energy from light is caught in chloroplasts.

Lignification Lignification is the process of lignin binding with cellulose and hemicellulose in the cell wall, thereby reducing their digestibility. Lignin is a complex polyphenolic compound that is an important structural compound in plants and that is resistant to microbial degradation.

Ligule A membrane that connects a grass leaf to its sheath.

Limiting amino acid The essential amino acid that is present in the lowest amount of a food source and thus restricts the total amount of protein obtained from that food.

Linseed oil Highly unsaturated oil that is contained in flax seeds and is used in paints and wood finishes.

Lipid synthesis inhibitor A selective herbicide that prevents the formation of fatty acids, which are important for lipid synthesis, and thus disrupts formation of cell membranes.

Lipids A class of organic compounds that includes fats and oils, which are high sources of energy for the human body.

Living mulch The system of planting annual grain crops into a living, but suppressed, perennial sod that is able to recover after the grain crop is harvested.

Lodging Refers to the toppling of the stems of a crop plant or stand.

Long-day plant Plants that flower when the photoperiod is longer than a certain period.

Longitude Describes the location of a place on the earth east or west of a north-south line called the prime meridian. Given as a measurement using 0° at the prime meridian to +180° eastward and −180° westward.

Low density lipoprotein (LDL) A complex compound of cholesterol, lipids, and proteins that transports and deposits cholesterol. LDL is considered a bad cholesterol because it deposits cholesterol in the arteries of the heart.

Lupine A high-protein legume that is native to the Mediterranean region. It can be fed to poultry, swine, and cattle, but is not widely grown because its main competitor, soybean, is more profitable.

Macronutrient Any essential elemental nutrient that is required in large amounts.

Malnutrition A nutritional situation where one or more essential nutrients are lacking despite sufficient caloric intake.

Maltose A two-glucose disaccharide found most frequently in germinating seeds during the breakdown of starch.

Marijuana An annual, herbaceous plant having hallucinogenic properties; grown as a psychoactive crop.

Mass selection A plant-improvement strategy in which individual plants with a superior, identifiable trait are selected from a population and used for the planting of the next generation.

Maturity groups A classification of soybean into 13 different groups based on photoperiod response. Each group is adapted to specific latitudes and growing-season length.

Mechanical pest management A pest management method that attempts to manipulate the crop's or plant's environment by using mechanical or physical means to make it less favorable to the pest.

Mechanical weed control Weed control performed with tillage implements.

Medicinal crop A plant species grown for medicinal purposes.

Meiosis A type of cell division in which the genetic content of the daughter cells is reduced by half. One cell undergoing meiosis produces four cells called *gametes,* each with half of the total genetic material of the parent.

Meristem An area of a plant with actively dividing and differentiating cells.

Mesophyll The tissue of the leaf between the upper and lower epidermis where photosynthesis takes place.

Mesophytes Plants that are adapted to both tropical and temperate regions and depend on precipitation for growth.

Mesopotamia An area of the Fertile Crescent that was a flat, flood plain bordered on the north by the Zagros Mountains and by the Arabian Desert to the south. It is the large area between the Tigris and Euphrates rivers in present-day Iraq. Because of the environmental diversity here, it was an optimal place for agriculture to develop.

Metabolism All the biochemical reactions throughout an organism and their regulation.

Metamorphosis The gradual developmental (growth) stages of an insect's life cycle from egg to adult.

Methane A greenhouse gas produced in fermentation reactions by ruminant animals such as cattle in manure-holding areas and wetlands.

Micronutrient Any essential elemental nutrient that is required in small quantities.

Mid-latitude climate A type of climate with either warm summers and mild winters or warm summers and cold winters.

Milk line A line that forms on corn kernels when the kernel is drying down and approaching maturity.

Mineralization The process of organic nitrogen being converted to inorganic nitrate by soil microorganisms.

Minerals Inorganic compounds that exist as positively or negatively charged ions; also can be components of larger compounds.

Mixed intercropping A type of polyculture in which two or more crops are grown together randomly. An example is an alfalfa-grass mixture or a perennial, prairie plant mixture.

Mode of action The biochemical mechanism herbicides use to kill plants. An example is a photosynthesis inhibitor.

Moldboard plowing The traditional primary tillage approach that shears off a section of soil and turns it over, incorporating crop residue into the soil but leaving the soil surface vulnerable to erosion and organic matter loss.

Molecular marker A segment of DNA that aids in the selection process of useful traits or alleles.

Mollisol A soil with an A horizon that is very fertile and high in organic matter. These soils are important for crop production and are found in the grasslands of the central United States.

Monocot A plant whose embryo has only one seed leaf or cotyledon.

Monoculture A system in which a single crop is grown in a field during the growing season.

Monoecious plants Plants that have separate male and female flowers on the same plant. Corn and wild rice are examples.

Monosaccharide Simple sugar; the basic building blocks of carbohydrates. They cannot be broken down into smaller compounds from reacting with water or human digestion; includes glucose, fructose, and galactose.

Morphology The study of the form and structure of plants.

Morrow plots Plots located on the University of Illinois–Champaign-Urbana campus where long-term agricultural research is conducted. This research site is one of the oldest agricultural research areas in the world.

Mulch Crop residue left on the soil surface.

Mulch tillage A tillage system that uses the chisel plow and minimal incorporation of residues.

Multiple cropping The production of two or more different crops in succession from the same piece of land in a year.

Mutation A permanent, heritable change in nucleotide sequence of a gene.

Mycoplasma-like organisms (MLOs) Microscopic organisms that are found in the phloem of a plant and cause plant diseases; also called *phytoplasmas*.

Mycotoxin A poisonous chemical produced by certain fungi that is harmful to people and animals when ingested.

National Organic Program (NOP) The federal program that regulates organic agriculture in the United States.

Nematode A microscopic (300–1000 micrometers), nonsegmented, roundworm that may be parasitic to plants or animals.

Neutron One of the three subatomic particles that make up an atom. Neutrons have no charge and are located in the nucleus of the atom.

Niche The specific range of environmental conditions including light, terrestrial or aquatic conditions, temperature, and nutrients to which a species is adapted.

Nicotinamide adenine dinucleotide phosphate (NADPH) A compound found in the chloroplasts. It is produced in the light reactions of photosynthesis and used in the Calvin cycle.

Nicotine An alkaloid found in tobacco. It is the active ingredient in cigarettes and is responsible for the addictive effects of tobacco.

Nitrate One nitrogen atom bonded with three oxygen atoms form NO_3. Nitrate is soluble in water and leached from the soil.

Nitrification The process of ammonium being converted into nitrate by soil bacteria.

Nitrogen credit The amount of nitrogen a legume crop provides to the subsequent crop.

Nitrogen cycle A cycle that describes the transition of nitrogen from atmospheric nitrogen to organic nitrogen.

Nitrogen fixation A biological process carried out by bacteria, some of which live in symbiosis with plants and some of which are free-living in the soil. Atmospheric nitrogen is converted into ammonium to be used by plants.

Nitrogen metabolism inhibitor A non-selective herbicide that impedes the enzyme that helps produce glutamine.

Nitrogen reservoir The amount of nitrogen available in an ecosystem. Plants are unable to use nitrogen in its elemental form (N_2) because it is very chemically inactive; therefore, the limiting nutrient is nitrogen.

Node The enlarged portion of the stem to which leaves are attached and where vegetative and floral buds develop.

Nodule A tumor-like growth on the roots of legumes caused by infection with symbiotic bacteria called *rhizobia*; the site of symbiotic nitrogen fixation.

Nonselective An herbicide that will kill almost all plants.

Nontarget Plants that are not the target of herbicide application but are sometimes affected.

No-till A tillage approach where specialized planters with disk openers slice through crop residues and precisely drop seed at the desired depth. This tillage has minimal crop residue disturbance and therefore minimizes soil erosion while maximizing soil organic matter and conserving soil water.

No-till grassland drill A type of seed-planting implement used to interseed pastures or grasslands.

Noxious weed An especially difficult-to-control weed that can injure crops, other useful plants, livestock, poultry, or other agricultural interests.

Nutrition The process of consuming food by humans not only for survival, but also for maintaining good health and fitness.

Nutritive value The content and availability of nutrients in a food.

Oat A small grain domesticated later than most other small grains. It is relatively high in fiber and protein content and is commonly used as a horse feed.

Obesity An extreme form of malnutrition where a person's body weight exceeds recommended levels by 20 percent or more.

Obligate parasite Organisms that require living host tissue to obtain nutrients for survival.

Oil Simple lipids from plants. They are liquid at room temperature.

Oil crop A crop that produces oils containing fatty acids in varying concentrations. Examples are canola and soybean.

Oilseed radish A brassica species used for oil production or as a cover crop.

Omega-3 fatty acids Acids such as linolenic acid that have significant health benefits and are not produced by human bodies. Therefore, they must be gained through foods such as meats and flax seed.

Opium poppy An annual, herbaceous plant grown as a psychoactive crop to produce opium.

Organic agriculture An ecological production system that encourages minimal use of off-farm inputs, the use of biodiversity, and other biological cycles and activity for crop and livestock production. Synthetic inputs cannot be used.

Organic certification The process in which an NOP-accredited certifying agency provides approval to an organic farmer that assures organic standards are being kept.

Organic fertilizer A fertilizer that is derived from living matter.

Organic matter The portion of the soil that includes animal and plant residues in varying stages of decay.

Organic system plan (OSP) A set of documents that describes an organic producer's practices and adherence to national organic standards.

Orographic effect Wet conditions on the windward side of mountains and dry conditions on the leeward side of mountains. This is caused when air is uplifted as it reaches the mountains and cools, precipitating its moisture on the windward side of the mountain.

Ozone layer The layer in the atmosphere that absorbs the ultraviolet light that is extremely harmful to humans and plants.

Parasitic flowering plant An obligate parasite that lacks a root system and instead uses a haustoria to absorb water and nutrients from its host.

Parenchyma A type of tissue where plant cells containing chlorophyll are sites of photosynthesis and energy storage.

Parent material The weathered rock from which soils are formed.

Pasture An area of land, usually fenced in, where plants are grown for grazing animals. Unfenced grazing areas are called *range*.

Pathogen An organism capable of causing disease.

Peanut A legume grown for its edible, underground seed. Peanuts are consumed whole as a snack food, as peanut butter, and in candy.

Pedigree selection A method of selection that is commonly used after hybridization. Plants are selected over multiple generations to produce a uniform product.

Peg The elongated ovary of the peanut plant which buries itself in the soil after pollination to form the peanut. Peanuts are harvested by digging the crop.

Perennial Plants that live for three or more years.

Perfect flower A flower that has both a stamen (male) and pistil (female) component.

Permanent wilting point The soil moisture at which a plant wilts because the water in the soil is unavailable to the plant.

Petal The showy, modified leaf of a flower important for attracting pollinators.

Petiole A leaf's stem by which it is attached to the plant.

Phenotype The observable characteristics of an individual plant that can be due to genotype, environment, or the interaction of both.

Phloem Part of a plant's vascular system that transports photosynthetic food products and carbohydrates from the leaves to other plant parts.

Phospholipid A type of fatty acid. An essential component of the membranes of plants.

Photoperiod The number of hours that light is present.

Photoperiodism Flowering or dormancy response of plants to changing lengths of day and night.

Photosynthesis A process in which plants use the energy they capture from the sunlight to produce sugars that are stored or used in respiration by the plant.

Photosynthesis inhibitor A type of herbicide that prevents plants from performing photosynthesis.

Physiological maturity The stage of development of grains when the maximum accumulation of dry matter in the seed has occurred.

Phytochrome Pigment in plants that detects the changes in proportion of red and far-red light.

Pigment inhibitor A selective herbicide that prevents plants from forming chlorophyll.

Pistil The female portion of a flower that contains the ovary, style, and stigma.

Plant disease Any deviation that interferes with a plant's normal development, appearance, or function and that progresses over time.

Plant growth regulator A chemical that regulates growth and development. Plant growth regulators generally act the same as many plant hormones, but are synthesized by people, rather than plants.

Plant hormone A chemical produced by plants that regulates growth and development.

Plant succession The naturally occurring, long-term changes in a plant community's structure.

Plantain An herbaceous tropical crop; its fruit is starchy and is cooked before it is eaten.

Planting date A recommended date that is optimal for crop establishment and that will maximize the capture of solar energy during favorable growing temperatures.

Planting depth The optimal depth at which a seed can germinate and emerge from the soil to grow.

Planting rates The number of seeds planted, or plants transplanted, so as to optimize the light interception and use of soil moisture throughout the growing season.

Pod corn A primitive type of corn in which each individual kernel is enclosed in a pod or husk. This type of corn is primarily used for ornamental purposes.

Polar climate This climate has extremely cold winters and cool summers and is not of any agricultural significance.

Polyculture Growing two or more crops together at the same time on the same piece of land; also known as *intercropping*.

Polyploid An organism that has more than one set of chromosomes.

Polysaccharide Organic molecule consisting of many monosaccharide units joined together that can function as energy storage or structural compounds.

Popcorn This corn has endosperm characteristics similar to flint corn, but the kernel is smaller. When heated, its soft starch has expansion properties that are unique compared to that of other soft, starch corns. It is commonly eaten as a snack food.

Pore space The area of space between soil particles that contain air or water. The larger the soil particles, the larger the pore spaces.

Postemergence Herbicide applied after the crop and weeds have emerged from the ground.

Postharvest Herbicide applied after harvest but before tillage.

Potato A bushy, annual plant grown for its starch-containing tubers. It is among the five most important crops in the world.

Precipitation Water that falls in the form of rain or snow.

Precision agriculture The use of technology including GPS and yield monitors to record site variability to aid in management decisions.

Preemergence Herbicides applied before the crop and weeds have emerged from the ground.
Preplant Herbicides applied before the crop is planted.
Price support program A financial payment provided by the United States Department of Agriculture (USDA), giving an incentive to grow specific crops.
Primary consumer A consumer who eats primary producers. Also known as *herbivores*.
Primary producer An organism that captures the sun's energy to produce its own chemical energy in the form of glucose. Examples are green plants and algae.
Primary tillage The tillage operation, usually the most aggressive one, that prepares the field bed for a subsequent crop.
Profile A vertical section of soil extending from the surface to the unweathered rock of the earth's crust.
Protein A complex substance made of amino acids; a vital part of human nutrition. It is found in plants and to a larger extent in meats.
Protein crop Crops such as soybean, peas, and peanuts that produce seeds naturally high in protein.
Proton One of the three subatomic particles that make up an atom. Protons have a positive charge and are in the nucleus of the atom.
Pseudoannual Perennial and biennial plants managed as annuals.
Pseudocereal A crop grown for its grain and used similarly to grains, but does not belong to the Grass family.
Psychoactive crop A plant grown for compounds that affect mental processes or moods.
Pulse Legume that has edible, high-protein seeds. These include soybeans, edible field beans, field peas, peanuts, and others.
Pure live seed (PLS) The viability of seed and its purity from weed seeds and other inert matter.
Qualitative Simple traits such as flower color that are controlled by one or only a few genes.
Quantitative Complex traits such as height and yield that are controlled by many genes.
Quinoa An annual, broadleaf, pseudocereal crop native to South America.
Ramie An herbaceous perennial grown as a fiber crop.
Rangeland A type of grazing land, usually in the drier, western part of the United States, where native vegetation is used for foraging livestock.
Reaper A machine that cuts (and sometimes binds) grain, depositing it on the field.
Red clover A short-lived perennial legume used for hay, silage, and pasture.
Refining The production process in which the white endosperm of flour is purified of germ and bran.
Resin A viscous liquid secreted by many plants, especially coniferous trees.
Respiration The conversion of sugars and starches to energy for use in metabolism of living cells.
Restricted use pesticide An herbicide or pesticide that is harmful to humans and the environment even when used as directed. Applicators of restricted use pesticides must be licensed.
Rhizobia Nitrogen-fixing soil bacteria that form symbiotic relationships with legumes.
Rhizome A stem that runs horizontally below ground and is a means of asexual reproduction of plants.

Rice One of the oldest and most widely cultivated crops in the world. It is a grass that grows best in extremely wet conditions.

Richness The number of species in an ecosystem or number of crops in an agroecosystem.

Ridge tillage A tillage approach in which ridges of soil (6 inches [15 centimeters] high) are created during final cultivation of a row crop, so that in a subsequent year, the crop can be planted directly into the ridge that becomes warmer and dries faster in the spring than surrounding soils.

Riparian buffer A strip of natural vegetation used to protect streams and other environments from adjacent agricultural areas.

Roller crimper A piece of equipment that rolls down cover crops while crimping to terminate the cover crop.

Root The plant organ responsible for anchoring a plant to the soil and for absorbing water and essential nutrients and minerals. Roots of some plants such as alfalfa, sugar beet, and sweet potato are also used for storage of energy reserves.

Root crop A crop grown for the starches stored in its roots.

Rotation effects Consequences resulting from crop rotations such as an increased yield in subsequent crops.

Rotational grazing The dividing of pastures into three or more sections and the moving of grazing animals from section to section, to regulate animal grazing and give pasture plants a rest between grazing events.

Roundup The brand name of glyphosate that is widely used because it kills a wide variety of weeds while not hurting resistant crops.

Row crop planter A type of drill that deposits seed in rows 20–30 inches (51–76 centimeters) apart with very precise seed metering that drops the seed at specific spacing within the row.

Ruminant An animal group that can digest cellulose. Their digestive system includes a multichambered stomach including the reticulum, rumen, omasum, and abomasum.

Rye A small grain crop that tolerates low fertility soils better than other small grains.

Safflower A relative of the sunflower that is grown to produce oil from its seeds, which is used for cooking and commercial purposes.

Sainfoin A perennial legume adapted to dry soils of the western United States; used as a hay and pasture legume.

Salinity The amount of soluble salts in a soil.

Saprophyte An organism that digests dead organic matter to obtain nutrients.

Saturated fatty acids Long-chain fatty acids containing only single bonds between carbon atoms (that is, they are completely saturated with hydrogen). Most animal fats are saturated fats.

Scientific name A binomial-naming system that allows for the universal identification of plants and animals. The name consists of two parts: the genus and the species. The scientific name is italicized, and the genus is always capitalized.

Sclerenchyma A type of tissue where plant cells that have thickened, lignified cell walls that provide structural support to the plant.

Season A division of the year based on changes in weather. The weather changes because of variation in the length of the day and the amount of solar radiation that reaches the earth's surface.

Secondary consumers Consumers that eat the primary consumers; also known as *carnivores*.

Secondary meristems Meristems that are responsible for lateral growth.
Secondary tillage The tillage operation performed after primary tillage that further prepares the seedbed for planting of the next crop.
Section A land measurement with an area of 1 square mile (640 acres; 259 hectares).
Seed The mature, fertilized ovule or egg within the ovary that contains a plant embryo.
Seed bank The reservoir of viable but dormant seeds in or on the soil.
Seed certification A process to ensure genetic uniqueness and quality of seeds and allow for orderly production of the seed for consumer use.
Seed dispersal The means by which seeds are moved to other areas away from the parent plant.
Seed dormancy A period when a seed is quiescent. Development of the embryo is temporarily suspended.
Seeding rate The number of seeds planted, assuming a certain level of mortality, to produce a plant population that will optimally use all resources available.
Seedling growth inhibitor A selective herbicide that affects the growth of roots and shoots of germinating seedlings.
Selection In plant breeding, the process by which breeders choose individual plants with superior characteristics from a larger population.
Selective herbicide An herbicide that affects only certain species of plants.
Self-pollination Occurs when plants are able to pollinate themselves. These plants are usually genetically homozygous.
Semiarid region Areas that get 10–20 inches (25–51 centimeters) of precipitation annually.
Semihumid region Areas that get 30–40 inches (76–102 centimeters) of precipitation annually.
Sepal The green, leaf-like structure located at the base of the petals of a flower.
Sheath The lower portion of a leaf that surrounds the stem (found in grasses).
Sheave A bundle of small grain stalks.
Shelling Separating corn kernels from the cobs.
Shelterbelt A windbreak barrier consisting of trees or shrubs planted to protect the soil from wind and other types of erosion.
Shock A bundle of grain plants.
Short-day plant A plant that flowers when the photoperiod is shorter than a certain period.
Shucking See *Husking.*
Sign In plant pathology, any structure or by-product produced by the pathogen that appears on or in the infected plant.
Silage High moisture forage that is stored anaerobically in a silo.
Silk The stigma and style of the corn plant.
Silvopasture A type of agroforestry-cropping system where trees, forage, and livestock coexist on the same land.
Simple leaf A leaf that has a single blade and petiole.
Sisal A native crop of Central America that is used to produce fiber for making twine, floor mats, and rope.
Small grain Grain crop whose seeds are small relative to corn seeds. These include wheat, oat, barley, and rye. The term is not generally used for small-seeded close relatives of corn, such as sorghum.

Soil The biochemically weathered, uppermost layer of the earth's crust. It is a unique ecosystem and an essential resource for the production and growth of plants and crops.

Soil fertility The ability of a soil to supply important chemical nutrients and essential elements to a plant.

Soil organism A biotic (living) entity that lives in the soil and is essential for nutrient cycling and overall soil functions. These include fungi, bacteria, earthworms, insects, rodents, snakes.

Soil texture The fineness or coarseness of a soil; it is determined by the type and amount of specific soil particles: sand, silt, or clay.

Solar energy Energy from the sun, which has a tremendous effect on the climate of the planet and is the driving force for photosynthesis.

Sorghum A vigorous, annual grass that resembles corn. It can be used for grain production, whole plant feeding to livestock, silage, ethanol production, or grazing. It is more tolerant of low rainfall than is corn.

Soybean One of the oldest cultivated crops, this legume has a number of different uses including vegetable oils, biodiesel, and protein for humans and livestock.

Species Each unique group of organisms is a different species. Individual members of a species share a similar genotype, phenotype, and environmental function.

Spelt A subspecies of wheat that is low in gluten and may be easier to digest.

Sprayer The mechanical device used to apply herbicides and pesticides to crops.

Spring equinox One of only two times a year when equal amounts of solar radiation reach both the northern and southern hemispheres. Spring equinox in one hemisphere is the same time as fall equinox in the other hemisphere. The hemisphere experiencing spring equinox will proceed to increasing solar radiation and longer daylight hours until summer solstice.

Sprinkler irrigation Irrigation system that applies pressurized water through sprinklers.

Stacked trait crop A transgenic crop with more than one genetically modified trait.

Stamen The male component of a flower, composed of a filament and a pollen-bearing anther.

Starch A glucose polymer that is the most consumed carbohydrate in human diets. It is the primary energy-storage form in corn grain and alfalfa roots.

Stem The main stalk or shoot of a plant found aboveground that provides the supporting structure of the plant as well as a channel for movement of water, nutrients, and products of photosynthesis.

Stocking rate The number of animals per acre on a pasture or range.

Stolon A horizontal, aboveground stem also called a *runner*. Plants use it to spread and produce new plants. An example is strawberries.

Stomata Very small openings in the epidermis of a plant that aid in the exchange of water vapor, carbon dioxide, and oxygen. Singular: stomate.

Storage The procedure by which products of the harvest are saved for future use after the completion of the crop production cycle.

Storage fungi Fungi responsible for reduction in the quality of grain during storage.

Stover The leaves and stalks of corn.

Stratosphere The layer of the atmosphere from 8–30 miles (13–48 kilometers). This layer contains the ozone layer.

Strip cropping A polyculture strategy in which different crops are grown in monocultures in adjacent strips. Contour strip cropping is a variation of strip cropping that is used for erosion control.
Strip tillage A tillage method where only a thin row is tilled and the remainder is left untilled. The crop is then planted into the tilled area.
Subsistence agriculture An agricultural lifestyle that provides only enough basic goods (food, shelter, and clothing) for survival.
Subtropical climate Moist, mid-latitude climate with mild winters.
Sucrose The most important disaccharide. It is composed of one glucose and one fructose. It is a widely used sweetener throughout the world and is known more commonly as *table sugar*.
Sugar beet One of the leading sugar crops in the world. It is grown for its root, which when harvested, contains between 18 percent and 20 percent sugar.
Sugarcane One of the leading sugar crops in the world. It is harvested for its cane (stem), which contains between 12 percent and 15 percent sucrose.
Summer solstice The longest day of the year. For the northern hemisphere this is 21 June; for the southern hemisphere it is 21 December.
Sunflower A native flower of North America, this plant is grown today for its seeds that can be used to produce oil for salad dressings and cooking. Seeds can also be eaten as a snack food.
Surface irrigation An irrigation system that uses gravity to distribute water.
Sustainable agriculture Agriculture that maintains soil and environmental resources for future generations and provides accountable and profitable production of food, fiber, or energy to meet societal demands.
Swathing The process in which the grains are mowed, deposited on the ground, and dried in the field.
Sweet corn Corn that has high sugar content and no starch. This type of corn is commonly eaten fresh because of its sweet taste.
Sweet potato A crop that stores energy as starch in modified roots. These roots also contain sugar, which results in the sweet taste; a good source of dietary Vitamin A.
Sweet sorghum A variety of sorghum that contains high stem sugar and is used for sugar production.
Sweetclover A legume not widely cultivated for harvesting but rather planted as a soil-conservation crop, because it grows rapidly and reseeds itself, or as a green-manure crop, because it can produce more nitrogen than any other legume.
Switchgrass A native, perennial, warm-season grass used for biofuel and forage.
Symptom A response by a plant to a pathogen that is visible to an observer; for example, stunting or leaf curling.
Systemic herbicide An herbicide that is taken up by the shoots or roots of the plant and then dispersed through the plant's vascular system.
Tall fescue A perennial forage grass native to Europe.
Tall fescue toxicosis A range of health problems in livestock caused by endophytic fungi in association with tall fescue.
Taproot A root system that consists of one large primary root with small, lateral roots.
Taro A tropical crop harvested for its starchy corm.
Tassel The male reproductive part of a corn plant.

Taxonomy A system of organizing all life based on similar genetic or morphological characteristics.

Temperate The zone that lies between the tropics and the Arctic or Antarctic Circles (that is, from 23.5° to 66.5° latitude north or south); has very distinct winter and summer seasons.

Temperature The measurement of the intensity of heat or energy content of the air, inert matter, or organisms.

Terrestrial plants Plants that grow on land.

Texture In soils, the fineness or coarseness that is due to the proportion of sand, silt, and clay particles.

Tillage A critical step in land preparation before crop planting. Tilling incorporates residues and fertilizers, manures, and lime; controls crop pests; provides a seedbed for seeding equipment; and alters the physical conditions and temperature of a soil.

Tiller Secondary stem that grows from the crowns of grasses. These stems have leaf parts and sometimes reproductive parts.

Tilth The beneficial qualities of soil relating to crop plant growth.

Tobacco An herbaceous, annual plant belonging to the Solanaceae family that is grown as a drug crop.

Topping Removing the flowers from a crop. Topping is necessary to maintain quality for crops such as tobacco.

Topsoil The A horizon layer of a soil profile, having the highest fertility and organic matter. Most plant roots and soil organisms grow in this layer.

Toxicity A measurement to describe how toxic or poisonous something is.

Trade name The brand name or name that is used to market an herbicide.

Trans fatty acids Long-chained fatty acids that have been partially hydrogenated, meaning hydrogen atoms had been added through heat and pressure to produce fatty acids with more saturation.

Transgenic Organisms that have had a desirable trait added to them through the process of genetic engineering.

Transpiration The loss of water from the interior of the leaves of a plant through the stomata.

Triticale A human-made grain species that is the result of crossing wheat and rye. Though it does have high grain-protein content, it lacks the breadmaking qualities of wheat and therefore is not widely grown.

Tropane alkaloids A group of alkaloids commonly found in the Solanaceae family. They have highly toxic properties.

Tropical Pertaining to the tropics, a region characterized by high temperatures.

Tropical climate Climate characterized by high temperatures, with an average temperature of 64°F (18°C) or higher. There is no winter season.

Tropical plant A plant that originated in equatorial regions.

Tropics Region characterized by high temperatures, with an average temperature of 64°F (18°C) or higher. There is no winter season.

Troposphere The layer of the atmosphere closest to the earth's surface. It extends upward 8 miles (13 kilometers). It contains the greatest concentration of the essential gases for humans and plants. Weather and climate also occur in this layer.

Tuber An enlarged, fleshy, underground stem that stores carbohydrates.

Tuber crop A crop grown for the starches it stores in its tubers; for example, potato.

Tundra A treeless plain in the polar regions.

Turnip A member of the Brassica family grown for its large, fleshy root. It was one of the earliest domesticated crops and can be cooked and consumed much like potatoes.

UG99 Stem Rust A particularly virulent strain of stem rust discovered in Uganda in 1999.

Undernutrition A nutritional state where an insufficient number of calories to maintain daily energy requirements is consumed.

United States Department of Agriculture (USDA) The part of the federal government responsible for the administration of federal programs related to farms and rural areas such as inspection programs that deal with food and crop production, import, and export; and for the promotion of research and education in the areas of agriculture and food systems.

Unsaturated fatty acids Long-chained, fatty acids that contain at least one double bond between carbon atoms, thus reducing the total number of hydrogen atoms in the molecule. Plants produce these fatty acids, although some fatty acids from plants can be saturated.

Vascular cambium A type of meristem that provides for an increase in stem diameter.

Vegetative The nonreproductive, aboveground portions of plants.

Venation The pattern of veins in a leaf; part of a plant's vascular system responsible for transportation of water and nutrients.

Vernalization A plant response to winter conditions of cold temperatures and reduced daylight; important for triggering flowering in the spring.

Vertical integration The business structure that occurs when a single firm controls several stages in the production of food and/or fiber.

Vetch An annual legume that produces trailing vines. They are excellent for green manures because they maintain higher nitrogen levels at maturity than other legumes.

Virus A submicroscopic (20–2000 nanometers) pathogen that is made up of nucleic acid and a protein coat. It requires a living host.

Vitamin A micronutrient, typically provided through diet, required by animals for good health.

Volatilization The process of urea in soils being converted to ammonium carbonate, then to ammonia.

Warm-season grasses Grasses that have optimum growth when temperatures are near 90°F (32°C); they have little growth below 50°F (10°C).

Water An essential part of life. Humans can survive only days without water. It composes approximately 60 percent of human bodies and as much as 90 percent in plants. Chemically, it is described as H_2O and can exist as a solid, liquid, or gas.

Water cycle The constant cycle through which the earth's water moves as it goes through solid, liquid, or gas states.

Wax A shiny coating that plants produce on leaves and fruit. It protects and reduces water loss.

Weather The short-term conditions and changes in a region's climate.

Weeds Plants that grow in places where they are unwanted or cause damage.

Wheat An annual small grain that is used to make flour and bread.

White clover A perennial forage legume that spreads by stolons.

Whole grain Products that include the entire grain kernel: the bran, germ, and endosperm.

Wild rice A cool-season, annual grass grown for its grain. It is native to the north central United States and central Canada, and is sacred to the Native people of those regions. Wild rice grain has high protein, carbohydrate content, and low oil content. It is widely used in prepared soups and dry mixes.

Wilted silage Hay crop silage that is dried less than haylage but more than direct-cut silage. Typical drying time is 4–8 hours. The moisture content is about 65 percent.

Winter solstice The shortest day of the year. In the northern hemisphere this is 21 December. In the southern hemisphere it is 21 June.

World population The number of people on the earth.

Xenia effect The immediate effect of one plant's pollen on the endosperm of a different plant's seed.

Xerophyte A plant that can grow in very dry areas because of special features including hairy leaves, thick cuticles, or a small leaf area.

Xylem Part of a plant's vascular system that transports water and minerals from the root system to other plant parts.

Yam A vine that stores energy in tubers. Yams are high in starch and energy and can be consumed directly by humans.

Yield stability In polycultures, if one crop dies, the other crop(s) can still produce a yield.

Zenith The point at which the sun is directly overhead. The sun's energy is most intense when it comes to the zenith.



Index

Page numbers followed by a "f" or "t" indicate the entry is included in a figure or table.

B

C

F

G

H

I

J

K

L

N

O

Q

R

S

T

U

V

W

X

Y

Z